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The
DESIGN OF ELECTRICAL MACHINERY.

-----oOo----

by

JOHN WALTER ESTERLINE, B.S.

Assistant Professor of Electrical Engineering, Purdue University, Associate Member American Institute of Electrical Engineers, Member American Society for Testing Materials.

Volume I.

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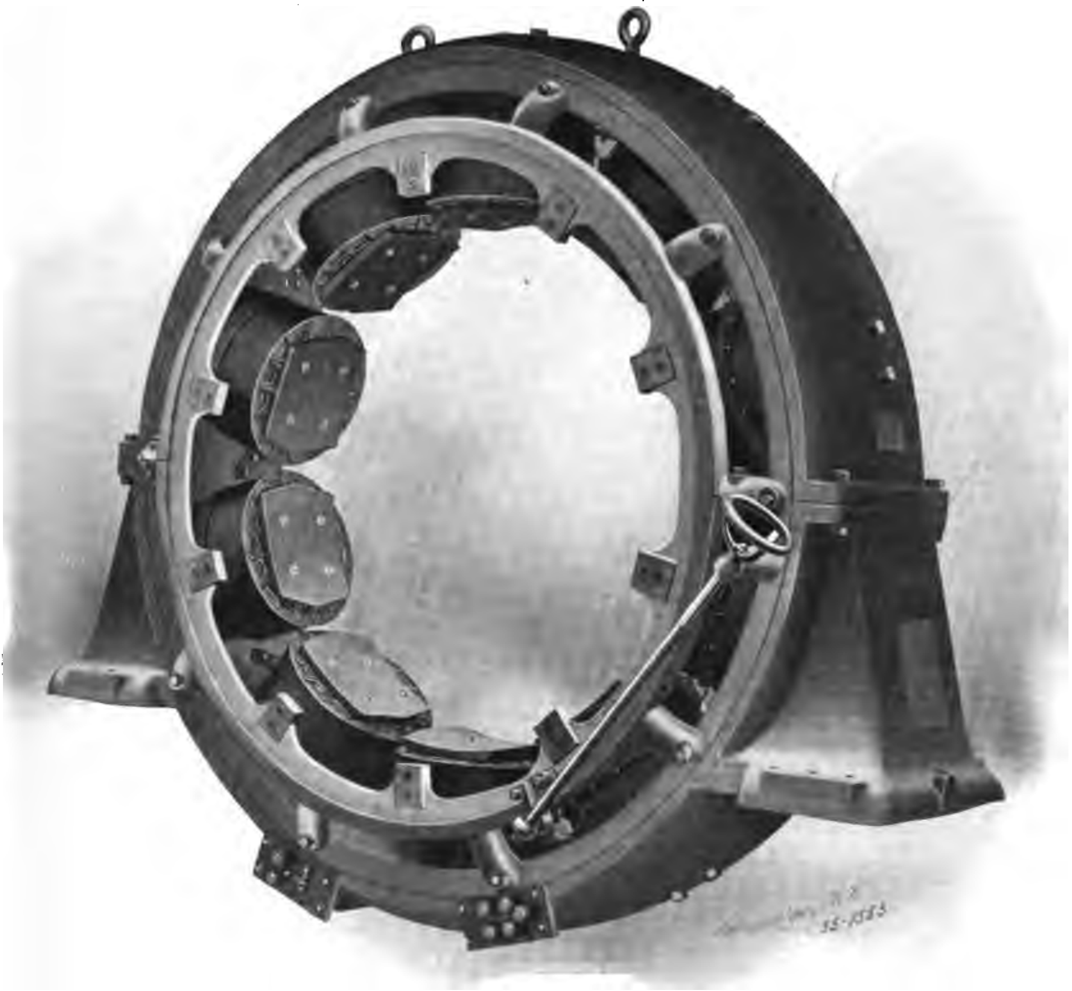

FIELD FRAME, 500 K. W., D. C. GENERATOR.

FRONTISPIECE.

PREFACE.

This volume has been prepared to serve as a text book in the study of the principles underlying the calculation of electrical apparatus and also to be used as a manual in designing electrical machinery.

In studying the subject, there are certain fundamental principles and phenomena of general application which must be comprehended before taking up the special branches of design. Most of these principles are thoroughly treated in the various text books on the different subjects, and a knowledge of this on the part of the student is assumed.

It is the intent of this volume to cover the design of Electromagnets, Electromagnetic Clutches and Brakes, Heating Apparatus, Rheostats, Direct Current Generators and Motors, Alternators and Alternating Current Motors, Converters and Transformers. Various sources of information have been sought, and the previous edition on this subject by W. E. Goldsborough and the author has been largely drawn upon. Where it is possible, the authorities have been mentioned and numerous references are given to guide those who may desire to make a more comprehensive study of a particular phase of the subject.

A large amount of original data, published here for the first time, have been added, and examples of the calculation of the various types of apparatus are given.

No apology is made for the form in which the book has been

issued. The rapid development of electrical apparatus and the consequent changes in the design of the same, make it both impracticable and inadvisable to issue a book in any but a flexible form. It is the purpose of the author to keep the work revised up to date with new editions as necessity may require.

The student should realize early that accuracy and good judgment must enter into the design which is to be of merit. A sense of the general fitness of things is essential. Electrical machinery is made to be sold. The good designer must not only make a machine of good economy, but also one which can be constructed and sold at a profit. An efficient monstrosity is not what is desired. The best design is one which will produce a machine of good economy, one which is substantial and cheap to construct and a marvel of simplicity.

LaFayette, Indiana, September, 1905.

PART ONE.

MATERIALS OF CONSTRUCTION.

In general, four classes of materials are used in the construction of electrical apparatus, namely , electric-conductors, insulators, magnetic conductors and those materials which go to make up the mechanical construction of the machine. As there are a variety of materials which may be used for each of the purposes mentioned, and further, since there are various grades of any one material, a knowledge of the characteristics and qualities of the various materials will be of value.

MAGNETIC MATERIALS.

The magnetic circuits of all electrical apparatus are made of iron in some one of its various forms. The most common of these are cast iron, cast steel, and sheet steel. The magnetic quality of iron varies considerably, depending both upon the chemical composition and the treatment received during the process of manufacture. For example, the addition of manganese to steel almost wholly destroys its magnetic properties. The hardening of sheet steel during the process of rolling, cutting and punching greatly increases its hysteretic constants, while annealing it tends to soften the iron, and if properly done, reduces the hysteresis loss. It will therefore be seen that a rather definite knowledge on the part of the designer of the materials which are to be used in the

magnetic circuits is essential.

PERMEABILITY TESTS.

With but few exceptions, the magnetic fields of electric machinery are produced by electromagnets, the result of magnetizing action produced by coils of wire in which a current flows. From the standpoint of efficiency and cost of copper, other things being equal, iron which has the highest permeability should be sought. In manufacturing electrical machinery, frequent tests of the iron are necessary in order to make sure that the quality is uniform and up to the required standard.

There are many methods of making these tests, some possessed of great accuracy, others giving results which are only reliable so far as the relative accuracy is concerned. The so called ring method, which consists of winding an annular ring uniformly with insulated wire to form a primary winding over which a secondary coil of fine wire is placed, has been much used. The primary winding is connected to a source of current through an adjustable resistance, an ammeter, and a reversing key, as shown in Fig. 1. The secondary turns are connected to a balistic galvanometer. A standard condenser, an earth coil, or a long solenoid must be employed to standardize the galvanometer.

The process of making the test is briefly as follows: Beginning with a small value of current in the primary, the reversing key is quickly thrown and the reading of the galvanometer, due to the charge induced in the secondary, is noted. When several readings have been thus taken, the current is increased in value, and readings taken as before. This process

is continued until the maximum value of current has been reached.

To calibrate the instrument, the current is sent through the primary winding of the calibrating coil and reversed as above and the readings of the instrument noted. In as much as the strength of the field in the calibrating coil is directly proportional to the current in its primary winding, a set of readings with one value of current is sufficient to standardize the instrument. The magnetic density of the specimen is calculated from the equation:- *

$$B = \frac{4\pi n\, n'\, a\, i_1\, R_2\, D}{10\, A\, T_2\, r_2\, d} \qquad (1)$$

$$\frac{4\pi n\, n'\, a}{10\, T_2\, r_2} \left(\frac{i}{A\, d} \right) R_2\, D \qquad (2)$$

where, n = number of secondary turns in the standardizing coil.

n' = number of primary turns per centimeter on the standardizing coil.

a = cross sectional area of standardizing coil.

T_2 = the number of secondary turns on the specimen.

Tr_2 = the resistance of the secondary circuit during standardization.

i_1 = current in the primary of the standardizing coil.

A = the area of the specimen in sq. cm.

R_2 = the secondary resistance during test.

d = reading of the galvanometer during standardization.

D = reading of the galvanometer during test.

As the flux in the iron increases, some provision must be made for keeping the galvanometer readings within the limits of the scale. This may be done either by inserting resistance

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* Trans. Amer. Society for Testing Mat'ls. Vol. 4, '04.

in serees with the galvanometer, or by decreasing the number of secondary turns. The latter method is preferable, as a change in the resistance of the galvanometer circuit alters the constants of the instrument. Fig. 5 illustrates a method of winding the secondary turns, making provision for varying the active number. The secondary coil is tapped at intervals and connected to small mercury cups. A second row of mercury cups is placed beside the first row, and between these, a resistance is placed which is equal to that of the winding connected between the opposite pair of terminals. By inserting a small connector between any pair of mercury cups, the desired number of secondary turns may be obtained, while the resistance of the circuit as a whole will remain unchanged.

To simplify the calculation, the secondary winding of the calibrating coil may be left in the circuit throughout the test, so that the resistance during the test and during calibration is the same. The values of R_2 and r_2 then disappear from the equation, which may now be written:-

$$B = 4\pi n n' a \left(\frac{i}{d A}\right) \frac{D}{T_2} \qquad (3)$$

The magnetomotive force H in Gilberts is expressed:-

$$H = \frac{4\pi N I}{10 L} \qquad (4)$$

Where, n = the number of turns on the ring,
l = the mean length of the magnetizing coil in cm. which in the case of a ring is equal to π times the mean diameter of the ring.

With sensitive apparatus in the hands of an experienced operator, the galvanometer method is productive of accurate results, but unless precautions are taken to preclude errors, the ring method is likely to give results which are not wholly

reliable.

Under the auspices of the committee appointed by the American Society for Testing Materials to investigate the magnetic properties of iron and steel, the author conducted a series of experiments with a view to investigating the reliability of the ring method as a means of testing iron. Experiments were made on a large number of rings of different diameters; various methods of standardizing the instruments were employed and the galvanometer controlled both by changing the secondary resistance and the number of secondary turns. The tes tests indicate that variable results may be obtained from the same iron by using rings of different sizes, the smaller rings giving the lower values. Variations of as much as 14 per cent. were obtained. In each case, the results indicated a very wide range in values obtained by the different methods of standardizing the galvanometer. A long solenoid, the length of which was eighty times its diameter, gave results which were consistent throughout. The tests further indicated the desirability of changing the number of secondary turns, keeping the resistance of the galvanometer circuit constant. Some of the rings tested and the results obtained are shown in Plates 1 and 2.

In the following pages are given the results of tests on a number of samples of cast iron, cast steel and sheet steel in use by manufacturing companies in this country. The results given in these curves were obtained by means of an instrument especially designed for this purpose, which is shown in Plate 3. The apparatus consists of an armature which is driven by a constant speed motor. The magnetizing coil constitutes the field winding, and the test bar forms the field core. The

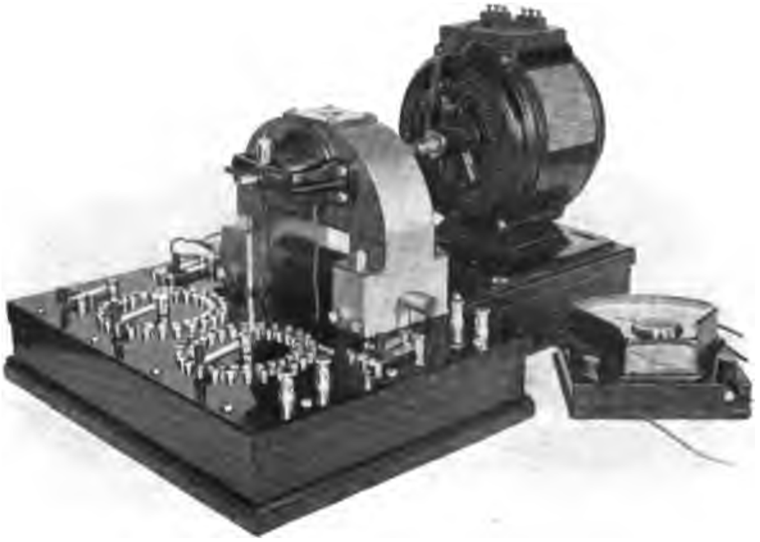

FIG. 7.

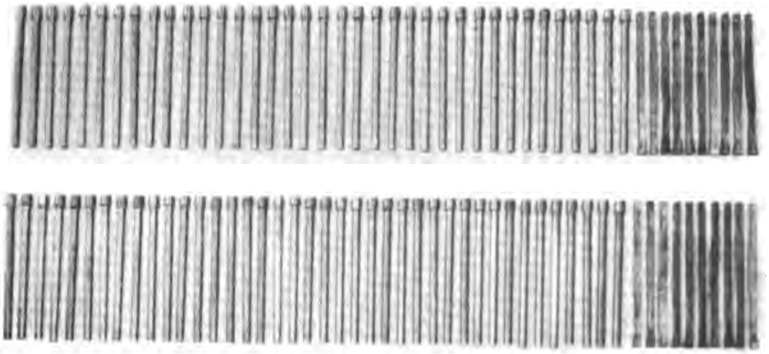

FIG. 8—SPECIMEN TEST BARS

magnetic density in the specimen is indicated by the readings of a direct current voltmeter, and the magnetizing force is indicated by the position of a dial switch, which changes the numberof active turns in the field winding. The reluctance of the air gap, poles and armature core is compensated for, so that the results are indicated directly without calculation. The permeability curve, hysteresis loop, permanent magnetism, and coercive force of a specimen may be obtained in two or three minutes with this apparatus.

Another method of testing the permeability of iron without the use of a balistic galvanometer is that devised by Holden. * The apparatus consists essentially of a pair of heavy iron yokes between which a standard and a bar to be tested are clamped. The rods are placed in parallel, and as near together as possible. Immediately above the bars is mounted a magnetometer, whose needle tends to lie at right angles to the axes of the bars. The two test bars are of the same cross section and when magnetized to the same density, the difference of potential between the clamping yokes would be zero, and the magnetometer needle will lie in its normal position. If the flux in one bar exceeds that in the other, a difference of magnetic potential will exist between the ends, and the leakage flux will tend to set the magnetometer needle at right angles to its zero position.

The process of testing consists in producing a balanced condition by varying the current in the exciting coils on one or both the bars. The B. & H curve of the standard bar having been previously determined, when the balance has been

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* Elec. World, June 27, 1895.

produced, and the magnetomotive force on the standard bar calculated, the value of B. in the test bar is found at once from the curve of the standard bar. The magnetizing force on the test bar, as well as that of the standard is calculated from the equation,

$$H = \frac{4\pi N I}{10 L} \qquad (5)$$

and since N and L are constants, we may write:-

$$\frac{4\pi n}{10 L} = K \qquad (6)$$

and $H = KI$.

In testing soft iron, this apparatus can be operated with little difficulty, but where residual effects are of considerable magnitude are encountered, considerable difficulty will be experienced in obtaining a balance.

HYSTERESIS AND EDDY CURRENT LOSSES.

When iron is subjected to a cyclic magnetization, energy is expended, due to the hysteretic effect and the eddy currents set up in the iron. The hysteresis loss which will occur in a sample of iron may be estimated by determining the hysteresis loop by means of the ballistic galvanometer. The method of testing is the same as the permeability test, except that instead of reversing the current, it is increased stepwise, readings of the instrument being taken for each increment of current When the maximum value of current has been reached, the current is decreased stepwise. When the zero value is attained, the reversing key is thrown and the current increased in the opposite direction. This operation is continued until the iron has been carried through a complete cycle. If these results

are plotted, an enclosed loop will be formed. By measuring the area of the curve, which may be conveniently done by means of a planimeter, and dividing this area by 4π, the quotient will be equal to the hysteresis loss of one complete cycle, expressed in ergs per cubic centimeter.

This hysteresis constant is valuable for the comparison of different samples of iron, but for use in calculation, it is desired to have the loss expressed in watts per pound per cycle per second. Since one cubic inch of iron weighs .282 pounds, and one cubic inch is equal to 16.4 cubic centimeters, the watts per cubic inch per cycle per second would be:-

$$\frac{\text{Area} \times 16.4}{10^7 \times 4\pi} \qquad (7)$$

and the watts per pound per cycle per second equal to:-

$$\frac{\text{Area} \times 16.4}{4\pi \times 10^7 \times .282} \qquad (8)$$

This method of testing by means of a balistic galvanometer is laborious and requires considerable calculation to derive the results, and for commercial work some method which gives the data directly is usually employed. The method of testing used should depend upon the use which is to be made of the iron.

Hysteresis loss in iron may be produced in two ways, one by subjecting the iron to a magnetizing force which passes through a zero value in changing from positive to negative, and the other way by subjecting it to a constant magnetization, which varies in direction. The core of a transformer is an example of the first case, and the armature of a generator or motor will serve as an example of the latter.

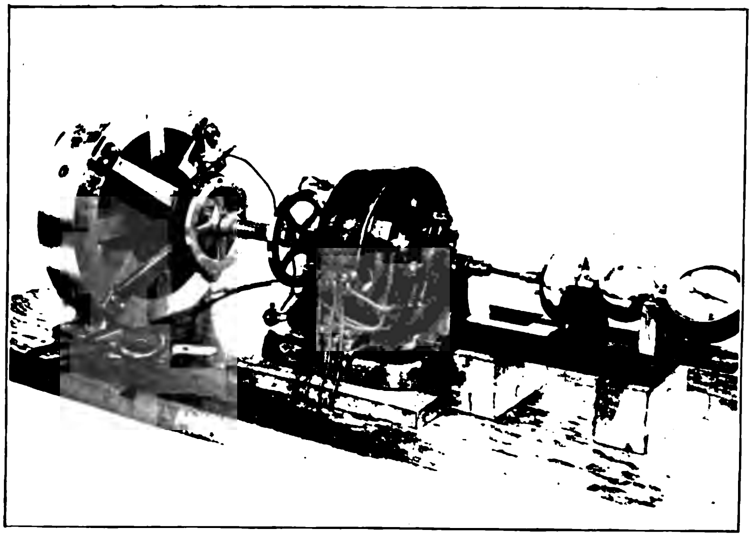

FIG. 9.

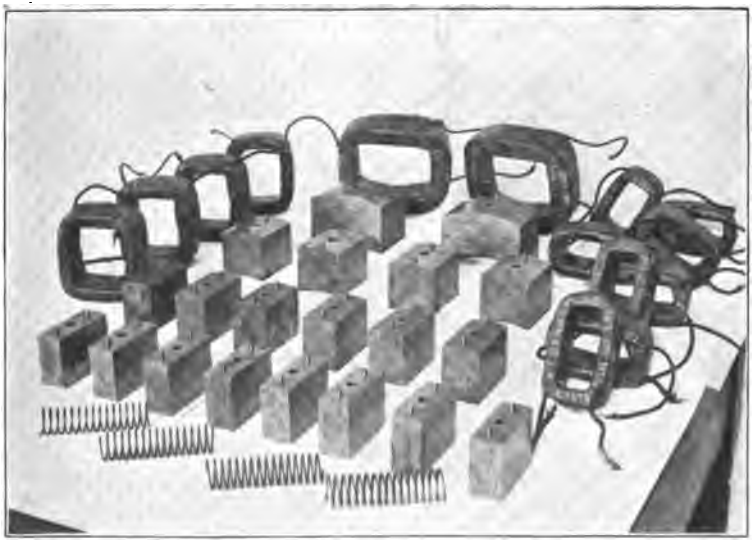

FIG. 11.

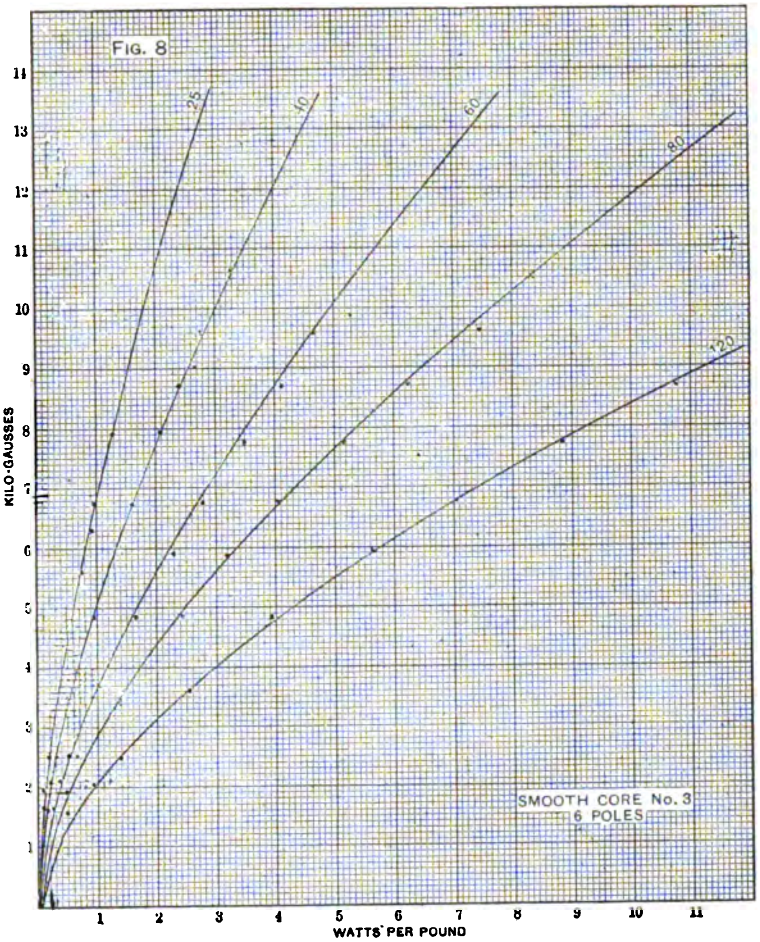
FIG. 8
KILO-GAUSSES
14
13
12
11
10
9
8
7
6
5
4
3
2
1
25
40
60
80
120
SMOOTH CORE No. 3
6 POLES
1
2
3
4
5
6
7
8
9
10
11
WATTS PER POUND

FIG. 12.

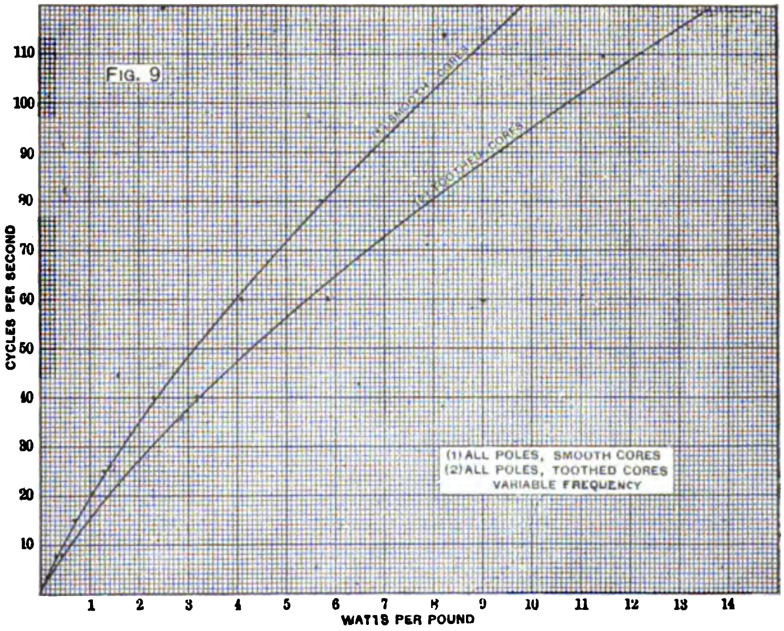
FIG. 9
CYCLES PER SECOND
110
100
90
80
70
60
50
40
30
20
10
(1) SMOOTH CORES
(2) TOOTHED CORES
(1) ALL POLES, SMOOTH CORES
(2) ALL POLES, TOOTHED CORES
VARIABLE FREQUENCY
1
2
3
4
5
6
7
8
9
10
11
12
13
14
WATTS PER POUND

FIG. 13.

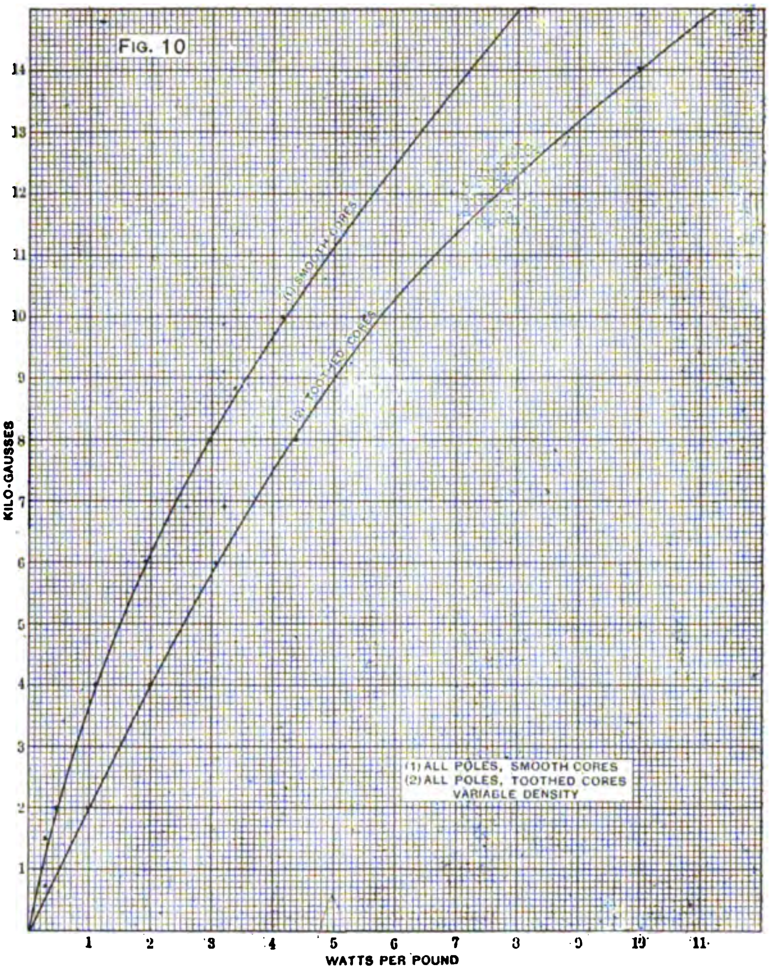
FIG. 10
KILO-GAUSSES
1
2
3
4
5
6
7
8
9
10
11
12
13
14
(1) SMOOTH CORES
(2) TOOTHED CORES
(1) ALL POLES, SMOOTH CORES
(2) ALL POLES, TOOTHED CORES
VARIABLE DENSITY
1
2
3
4
5
6
7
8
9
10
11
WATTS PER POUND

FIG. 14.

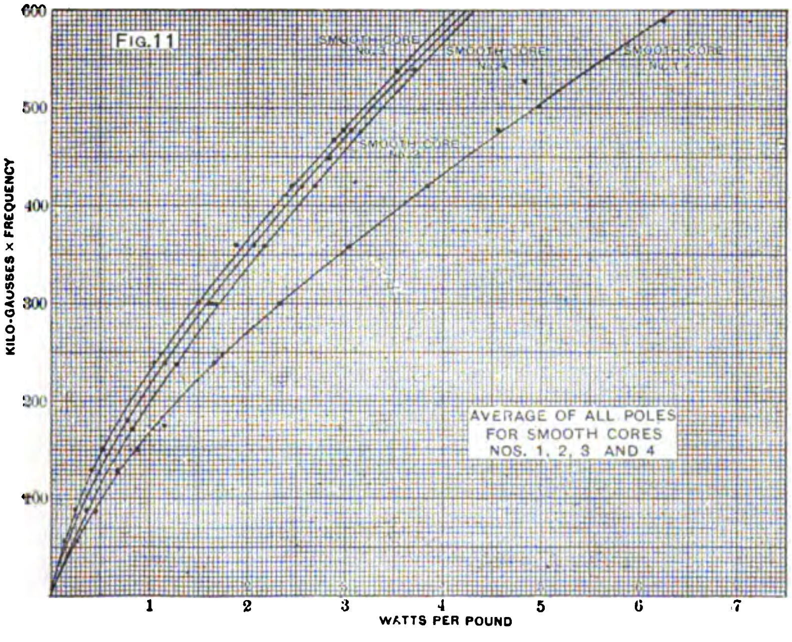
FIG. 11
KILO-GAUSSES × FREQUENCY
100
200
300
400
500
600
SMOOTH CORE NO. 3
SMOOTH CORE NO. 4
SMOOTH CORE NO. 1
SMOOTH CORE NO. 2
AVERAGE OF ALL POLES
FOR SMOOTH CORES
NOS. 1, 2, 3 AND 4
1
2
3
4
5
6
7
WATTS PER POUND

FIG. 15.

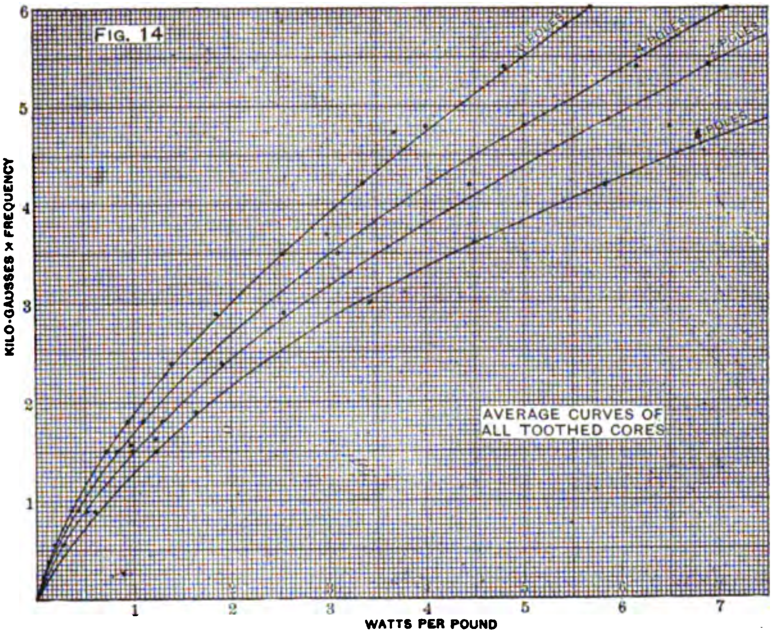
FIG. 14
POLES
POLES
POLES
POLES
AVERAGE CURVES OF
ALL TOOTHED CORES
KILO-GAUSSES × FREQUENCY
6
5
4
3
2
1
1
2
3
4
5
6
7
WATTS PER POUND

FIG. 16.

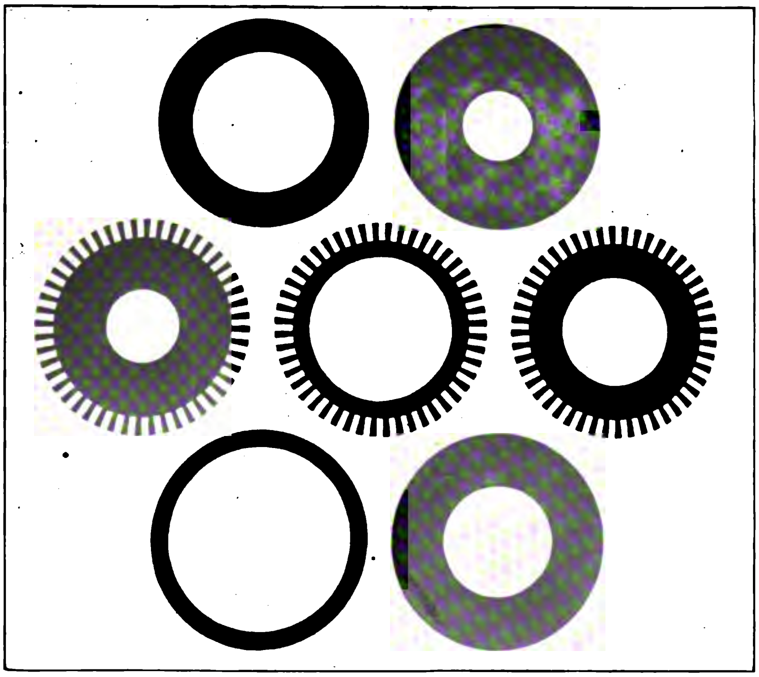

FIG. 10.

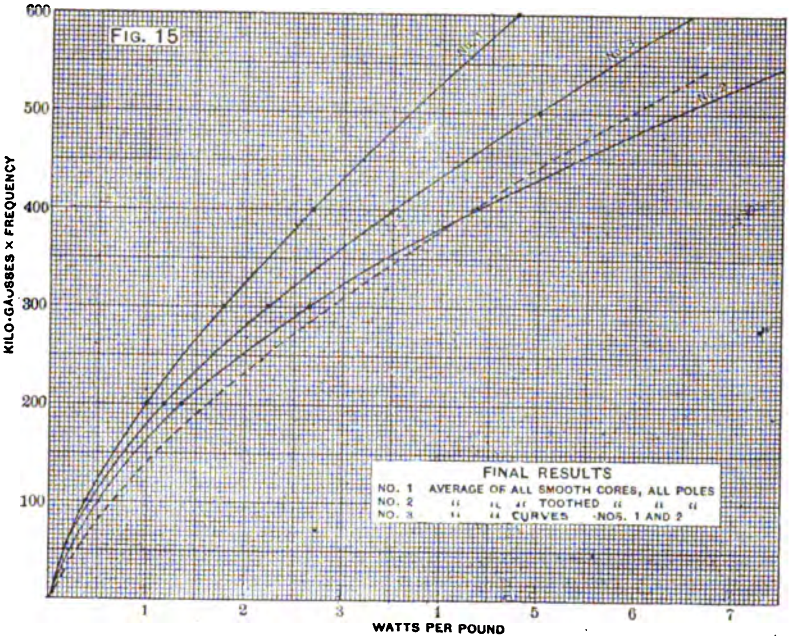
FIG. 15
NO. 1
NO. 3
NO. 2
FINAL RESULTS
NO. 1 AVERAGE OF ALL SMOOTH CORES, ALL POLES
NO. 2 " " " TOOTHED " " "
NO. 3 " " CURVES NOS. 1 AND 2
KILO-GAUSSES × FREQUENCY
600
500
400
300
200
100
1
2
3
4
5
6
7
WATTS PER POUND

FIG. 17.

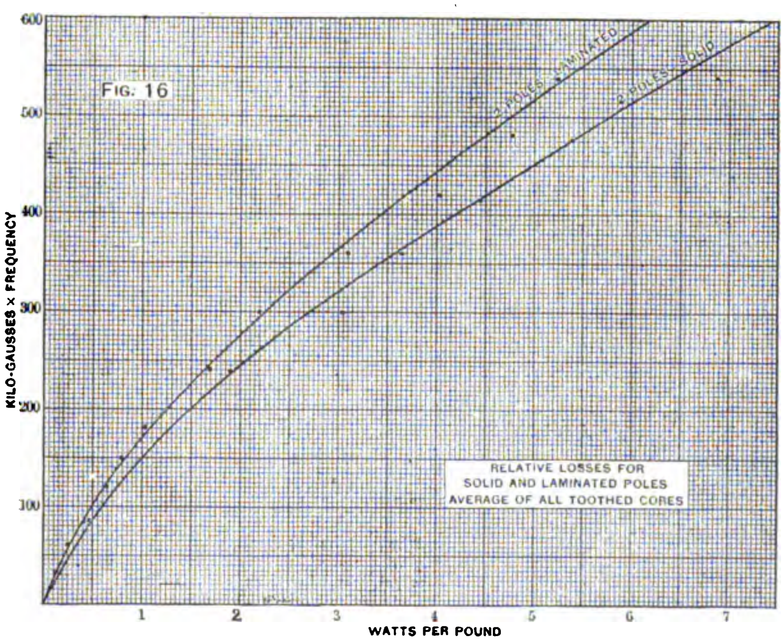
FIG. 16
2 POLES LAMINATED
2 POLES SOLID
RELATIVE LOSSES FOR
SOLID AND LAMINATED POLES
AVERAGE OF ALL TOOTHED CORES
KILO-GAUSSES × FREQUENCY
600
500
400
300
200
100
1
2
3
4
5
6
7
WATTS PER POUND

FIG. 18.

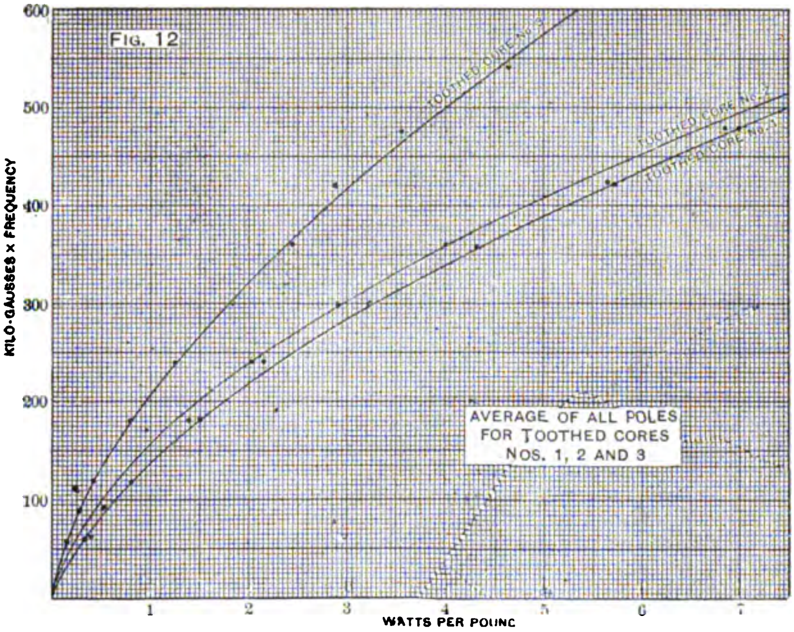
FIG. 12
TOOTHED CORE No. 3
TOOTHED CORE No. 2
TOOTHED CORE No. 1
AVERAGE OF ALL POLES
FOR TOOTHED CORES
NOS. 1, 2 AND 3
KILO-GAUSSES × FREQUENCY
100
200
300
400
500
600
WATTS PER POUND
1
2
3
4
5
6
7

FIG. 19.

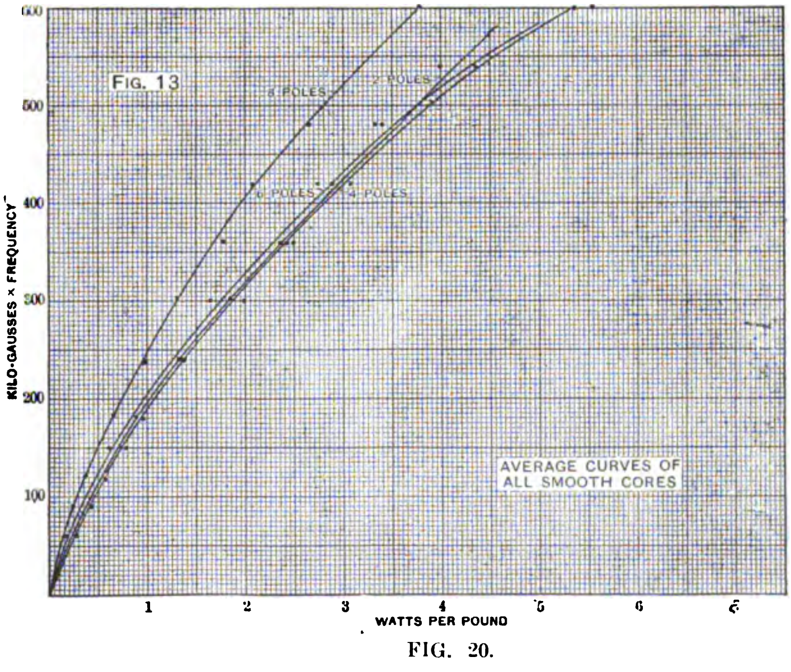
FIG. 13
8 POLES
2 POLES
6 POLES
4 POLES
AVERAGE CURVES OF
ALL SMOOTH CORES
KILO-GAUSSES × FREQUENCY
100
200
300
400
500
600
WATTS PER POUND
1
2
3
4
5
6
7

FIG. 20.

Steinmetz has shown experimentally that the hysteresis loss is a function of the maximum density to which the iron is carried during a cycle, and since in both armature core and transformer core the magnetization is never quite uniform, the hysteresis loss is difficult to calculate, and the sample tested should bear a close relation tothe form in which the iron is to be used.

In an endeavor to determine the effect of variable distribution of flux, frequency of magnetization, number of poles, etc., the apparatus shown in Plate 4 was constructed and a number of sheet iron cores provided. Each core was tested at a number of average densities and under a different number of poles, ranging from two to six. Cores of the same depth, but with and without teeth in the periphery were also tested, and these underboth laminated and solid poles. The results of the tests will be found on Plates 5, 6, 7 and 8, as follows:-

Fig. 12 is the form in which the original data was plotted, the curves being drawn for each test at the different frequencies with watts loss per pound as abcissas and kilo-gausses density as ordinates.

Fig. 13 shows the difference in the loss of the smooth cores, with watts per pound as abcissas and cycles times kilo-gausses as ordinates.

Fig. 14 shows the relation between the smooth and toothed cores at different densities.

Fig. 15 shows the average losses under all the poles for the different smooth cores.

Fig. 16 shows the average losses of all the toothed cores under the different poles.

Fig. 17.

Curve No.1 gives the average results of al the smooth cores under al the poles.

Curve No. 2 gives the average of al the toothed cores under all the poles.

Curve No. 3 is the average of curves No. 1 and No. 2. The difference between curve No 1 and curve No. 2 shows the increase in the core loss due to the higher density in the teeth and the eddy current losses in the poles.

Fig. 18 shows the difference between the losses of toothed cores under the solid and laminated poles, so that the difference between these two curves indicates the reduction in loss which may be obtained by carefully laminating the poles.

Fig. 19 shows the losses in the different toothed cores under all the poles.

Fig. 20 shows the losses of the smooth cores under different numbers of poles.[*]

TESTING TRANSFORMER IRON.

The core loss of transformers should be kept as low as is practicable, as the transformers are operating at no load the majority of the time. Especially is this true of transformers used for electric lighting. It will be found advisable to make frequent tests of the iron used in transformer construction, and a method of testing applicable to commercial work should possess the following characteristics:-

First: Sample should be easily, quickly and inexpensively prepared.

Second: The method of testing should be rapid, and yet give high relative accuracy and fair absolute accuracy.

Third: Apparatus should be simple and unaffected by vibrations, magnetic fields, etc.

Fourth: Instruments should be direct reading, requiring little or no calculation in deducing results.

Fifth: Sample should conform as nearly as possible to the shape of the stampings to be used, especially if high absolute accuracy is desired.

The apparatus shown in Fig. 21[†] was designed with a view of embodying as nearly as possible all the features which have just been set forth. It consists of two non-conducting shells, each containing one half of a magnetizing coil, so constructed

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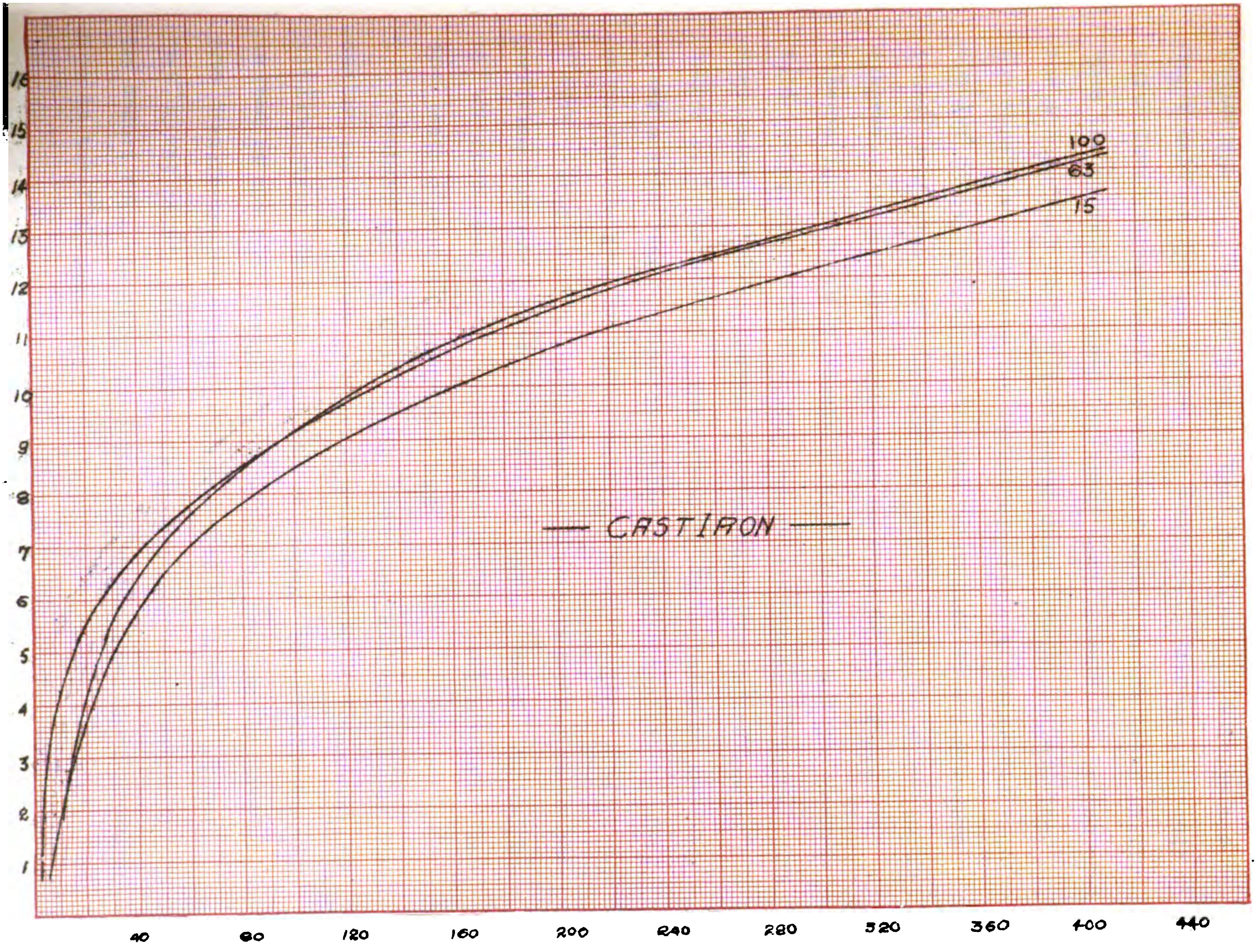
[*] "The Factors Which Effect the Energy Losses in Armature Cores" J.W.Esterline and C.E.Reid, Trans. A. I. E. E. Vol. XX, 1903.

[†] "A Direct Reading Apparatus for Testing Transformer Iron" by J. Walter Esterline, Trans. A. S. T. M. Vol. 3, Page 288.


16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
40
80
120
160
200
240
280
320
360
400
440
100
63
15
— CASTIRON —

that the two halves may be readily taken apart and placed together again. The two ends of each half turn of wire in the upper half of the encasement fit accurately into mercury cups which form the terminals of the half coils in the lower shell. When the parts are closed together, each convolution is restored and the current finds a continuous path through the winding. The apparatus shown in the illustration was made for testing annular rings, but the design can be adopted to any standard transformer stamping. The connections are made as shown in the diagram, the wattmeter being used to measure the losses. An alternating current of constant value is used, and the magnetizing value varied by changing the active number of turns. The resistance of the apparatus remains constant, regardless of the number of turns active The wattmeter is adjusted so that it gives a zero reading when the current is adjusted to its normal value with no iron in the apparatus. When the iron core is placed within the coil, the reading of the wattmeter above zero position indicates directly the iron loss in watts. The weight of the core used is ten pounds, so that the loss per pound is one tenth of the wattmeter readings.

Another apparatus which has been used successfully by the author is illustrated in Fig. 22 and consists of a transformer winding, into which the core can be placed. The iron to be tested is cut into strips 1-1/2" wide and used as the core of the transformer, the loss being measured by means of an indicating wattmeter. In using this apparatus, it is necessary to deduct from the total loss the energy expended in the winding due to the I^2R loss.

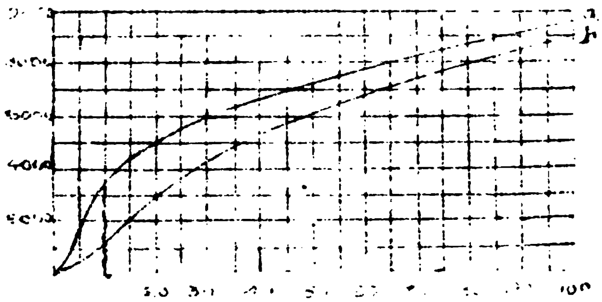
PROPERTIES OF IRON AND STEEL.

It is well known that the magnetic quality of iron and steel depends upon the physical structure, which may be varied to a degree by annealing, tempering, continued heating, etc. While it is impossible in most cases to establish any law governing the same, the magnetic properties depend to a degree upon the chemical content of the metal and the effect of any one of the processes mentioned above depends to a great degree upon the chemical composition. Iron which has been rapidly cooled, either in the form of a casting or in the process of rolling, will have its magnetic quality impaired. This may be restored in a degree at least by careful annealing. The effect of the different elements which may be found in iron and steel is dependent in some degree upon the percentage of those elements, although as has been stated, no law has as yet been established, and probably never will be on account of the fact that the effect of one element is influenced by the presence of another. Experiment shows that iron having the highest permeability does not always possess the lowest hysteretic loss. Usually iron which is low in carbon and practically free from sulphur, manganese and phosphorus will show a high permeability, provided the physical treatment has not been of a nature to impair its quality, but this same metal usually has a higher hysteretic loss than a mixture containing more impurities.

CAST IRON.

In cast iron, the permeability depends largely upon the percentages of the impurities contained. In making sheet

steel for armatures and laminated pole pieces, and steel castings where high permeability is required, it is endeavored to keep the amount of elements other than iron as low as possible. Sheet steel can be made with as high as 99.7 % iron, while the regular casts of some castings contain more than 99.6 % iron. In these purer steels, the magnetic properties are dependent more upon the mechanical and heat treatments to which the iron is subjected than upon the chemical composition. In cast iron, other elements are present in a far greater degree, and are a factor in determining its magnetic qualities. Of carbon, which exerts the most influence on the permeability there is found frequently more than 3.5 % existing in two states, graphitic and combined. The amount of combined carbon depends upon the rate of cooling, and the presence of other impurities.

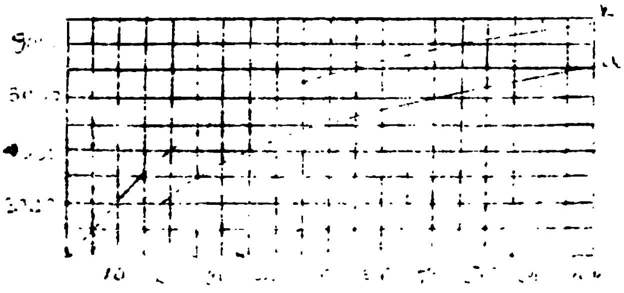


	Si.	S.	P.	Mn.	C.C.	G.	T.C.
a.	2.80	.077	.794	.59	.05	3.29	3.34
b.					.91	2.43	3.34

Fig. 23.

In the frames of larger machines, the strength and rigidity of the metal is of prime importance, while in medium and small sized frames, the problem of strength is almost, if not entirely eliminated and the permeability is more important. The amount of sulphur should be kept as low as possible, and while the percentage of sulphur in ordinary cast iron is small and therefore it of itself does not noticeably effect the permeability, it is however indirectly very detrimental, as it tends

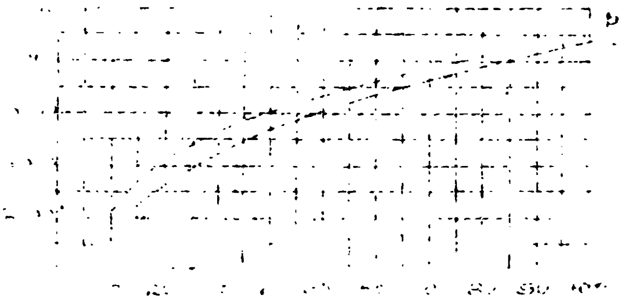
to increase the combined carbon, as well as to cause blow holes. The effect of sulphur in combining the carbon may be neutralized by adding a larger amount of silicon.



	Si.	S.	P.	Mn.	G.C.	C.C.	T.C.
a.	2.50	.039	.645	1.40	3.26	.31	3.57
b.	2.50	.080	.645	.59	3.02	.38	3.40

Fig. 24.

Phosphorus in cast iron varies from .15 % to 1.4 % and in ordinary castings is about .5 %. The presence of phosphorus in this amount will not seriously effect the permeability. With manganese, it is quite different, for its presence in large amounts seriously effects the permeability. In Fig. 24 are given two curves of cast iron with their chemical composition. These curves show clearly the detrimental effect of manganese.

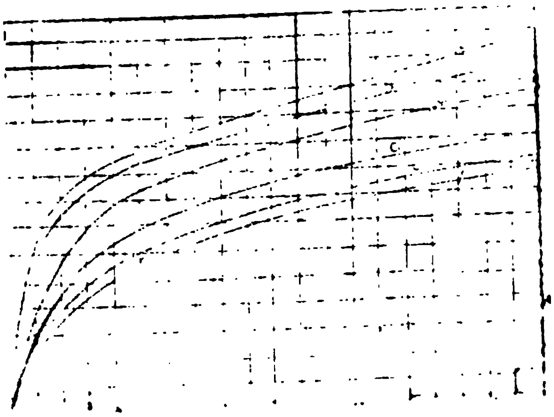


	Si.	S.	P.	Mn.	C.C.	G.	T.C.
a.	1.46	.046	.447	.46	.70	3.01	3.71
b.					.45		

Fig. 25.

The percentage of carbon existing in cast iron as graphite or combined carbon depends upon the amount of manganese, sulphur and silicon present, the size of the casting and rate of cooling. With enough silicon in the iron, the combined carbon can be reduced to .1 %. The silicon of itself has very little detrimental effect upon the permeability, so that it would seem best to have a large percentage of silicon, which will also insure a soft casting. The curves in Figs. 23 and 25 illustrate this clearly. Curves a. and b. Fig. 25

are from bars cast from the same ladle of iron, as are also curves a. and b. Fig. 23 The higher combined carbon in a., Fig. 25 and a., Fig. 23 was obtained by a faster rate of cooling. In Fig. 26 will be found a series of curves showing the effect of various percentages of graphitic carbon, the other elements being fairly constant. It is singular to note that instead of increasing in direct proportion as graphite is decreased, the permeability is the lowest when the graphite is about 2 %, while the effect on the permeability due to the presence of graphite is considerably smaller in iron having from 2-1/2 % or less than 1.7 % of graphite.

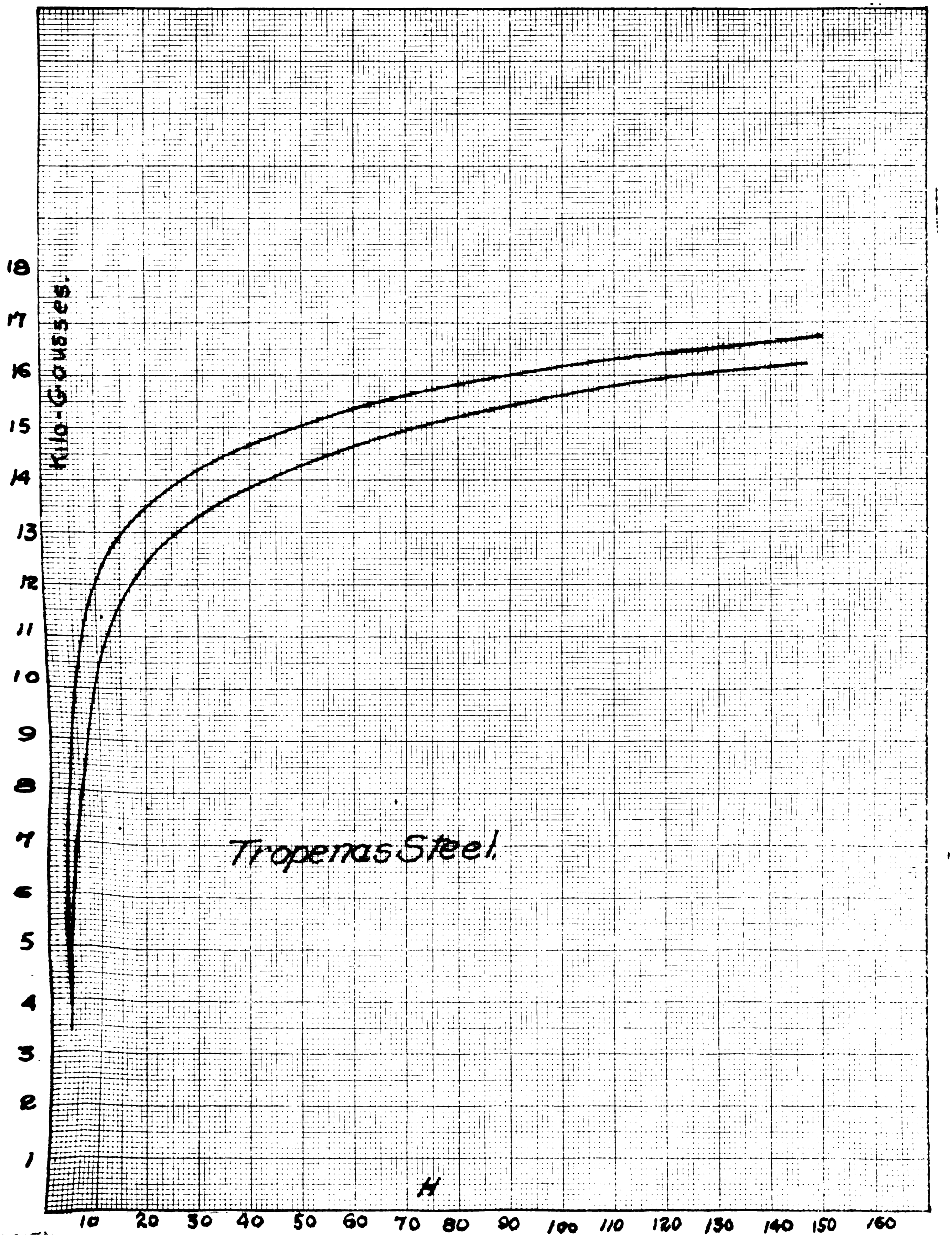


	Si.	S.	P.	Mn.	C.C.	G.	T.C.
a.	2.99	.048	.542	.54	.06	3.51	3.57.
b.	2.97	.057	.578	.56	.04	3.28	3.32
c.	4.83	.097	.661	.55	.03	2.34	2.37
d.	4.28	.089	.490	.43	06	1 92	1.98
e.	4.39	.102	.632	.47	.02	1.79	1.81
f.	5.48	.068	.493	.50	.03	1.44	1.47

Fig. 26.

CAST STEEL.

The high permeability and uniformity with which cast steel can be made has led to the use of great quantities of it in the manufacture of electrical machines. Its magnetic properties are such that when desirable, it can be worked at magnetic densities more than double that which would be economical in cast iron, which greatly reduces the weight of the parts. The uniformity with which steel castings can be made leaves little to be said with regard to the influence of the elements upon its


Kilo-Gausses.
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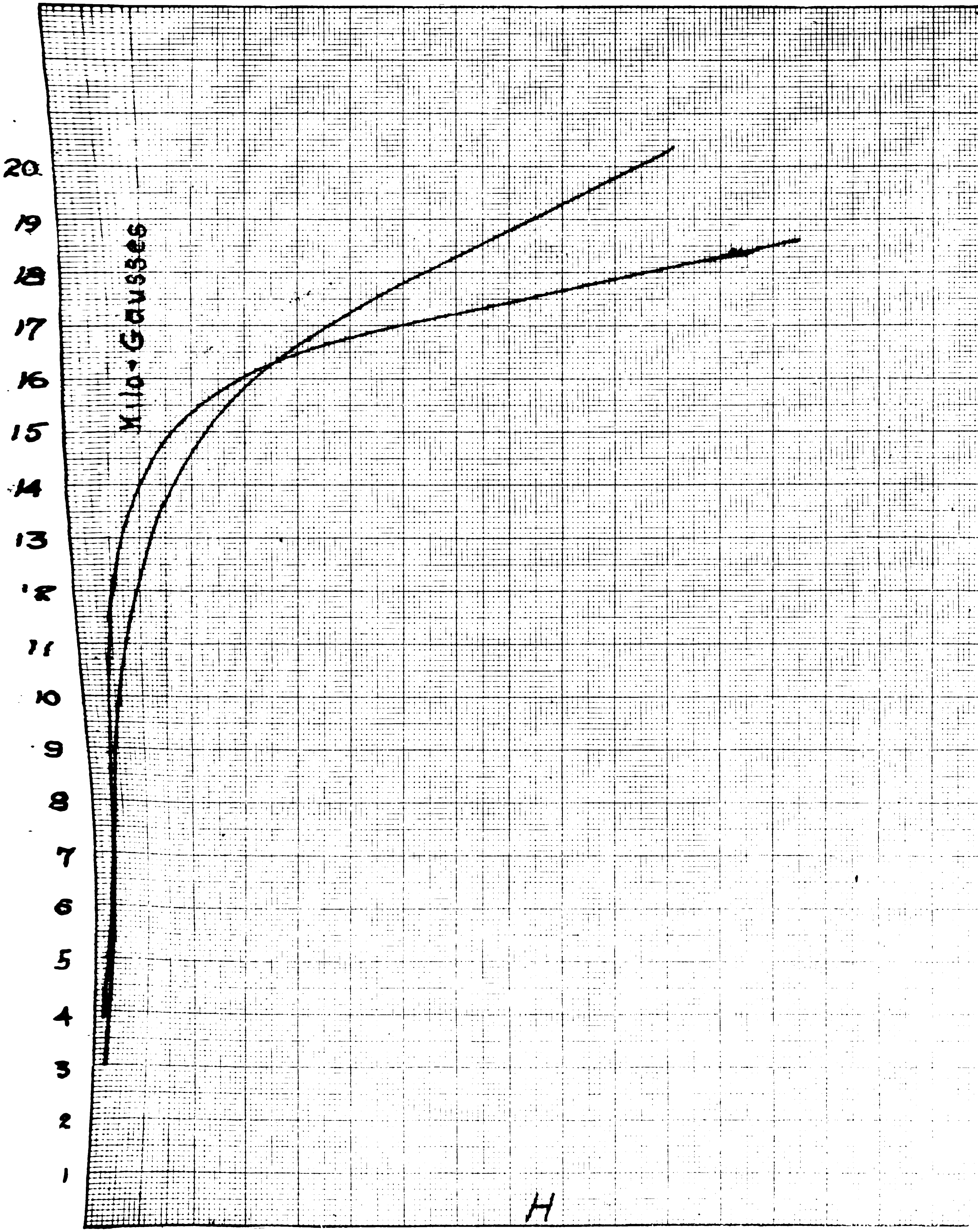
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Kilo-Gausses
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magnetic qualities. In tests of more than 100 samples of steel from different manufacturers, very few specimens have been found which were not well suited for electrical purposes in general The more nearly free from all impurities, the higher the permeability and the better the steel is adapted to electrical work. Of all the samples tested, those giving the highest permeability were of the following composition.

Carbon,	0.09
Manganese,	0.04
Silicon,	0.05
Sulphur,	0.071
Phosphorus,	0.057
	0.308

In steel, carbon is the most objectionable impurity, and should never be allowed to exceed .2 %. Small percentages of silicon are not objectionable, and will increase the permeability at lower densities. Large percentages of silicon will lower the permeability at high densities and render the steel harder, making it difficult to machine.

Percentages of phosphorus under .1 % and manganese less than .3 % are not objectionable, but larger percentages than those named impair the quality of the steel magnetically.

SHEET STEEL.

Sheet steel as produced in this country is nearly pure iron, and its magnetic quality is dependent almost entirely upon the treatment to which it is subjected. The strains produced in the process of rolling, punching and machining reduce the permeability and increase the hysteresis loss, although the iron may be restored by a process of annealing.

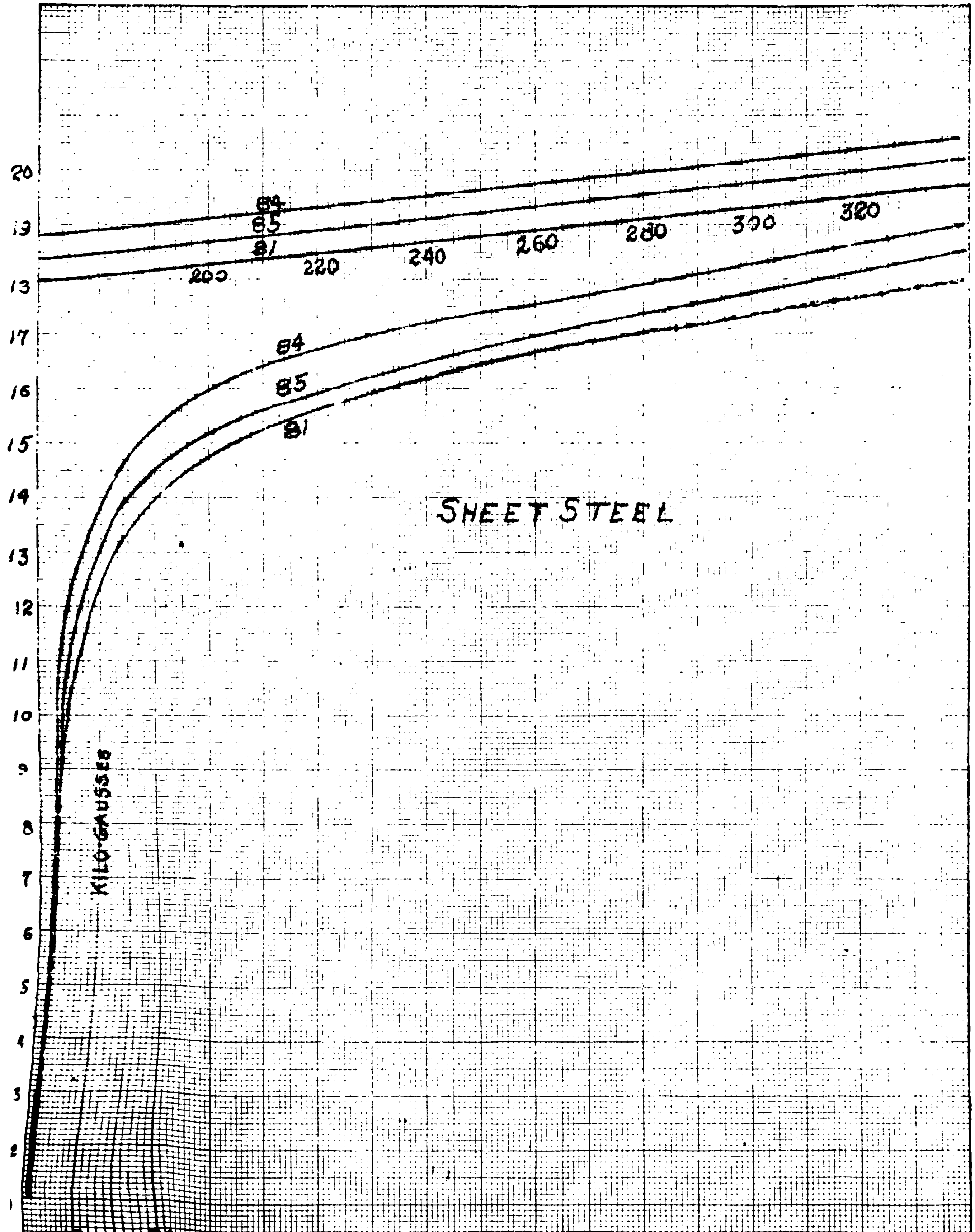
The temperature at which the annealing is done has a marked influence upon the results. As the temperature at which

annealing is done is increased, the iron is improved until about 900 degrees Centigrade is reached. Temperatures above this value should not be employed, as they deteriorate, rather than improve the iron. The tests of a large number of samples of armature and transformer iron produced in this country show an exceptionally wide variation in quality, which indicates clearly the necessity of the exercise of care in the process of manufacture and the annealing.

The thickness of the sheets in use varies from .014 in. to .03 in. The thinner sheets are used in transformers, usually from .014 in. to .018 in. The thicker sheets are used in armature cores. The hysteresis loss increases with the density, and is directly proportional to the frequency of the magnetization and is independent of the thickness of the sheets. The eddy current loss increases with the thickness of the sheets and is approximately proportional to the square of the density and the frequency.

The teeth of slotted armature cores are generally worked at a very high degree of saturation. In calculating the reluctance of a magnetic circuit formed by the teeth and the slots, recourse should be had to curves showing the relation between B. & H. in the steel at very high densities.

The apparatus shown in Fig. 27 was designed and constructed for the purpose of testing sheet steel above saturation. The apparatus consists of a heavy magnetic circuit built of laminated iron. The poles are brought very near each other, and the pole faces are tapered down to one sixteenth the cross section of the magnet frame. Exciting coils capable of producing a very high m.m.f. were wound and placed on the frame. The


SHEET STEEL
KILO-GAUSSES
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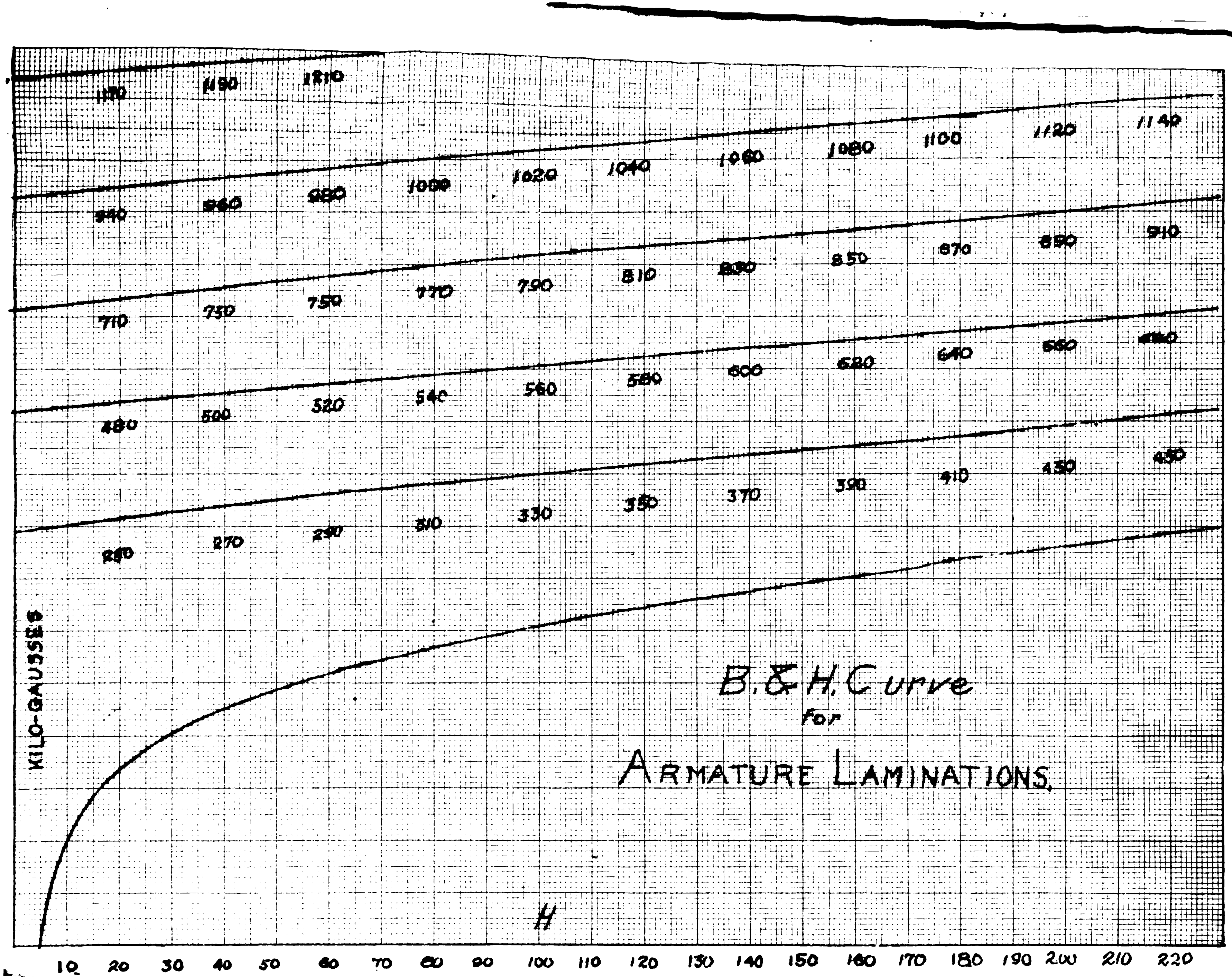


B. & H. Curve
for
ARMATURE LAMINATIONS.

specimen consists of a number of laminations two centimeters long and one centimeter wide, enough being laid up to make the sample one centimeter thick. These are placed between the pole faces, this distance being equal to the length of the specimen.

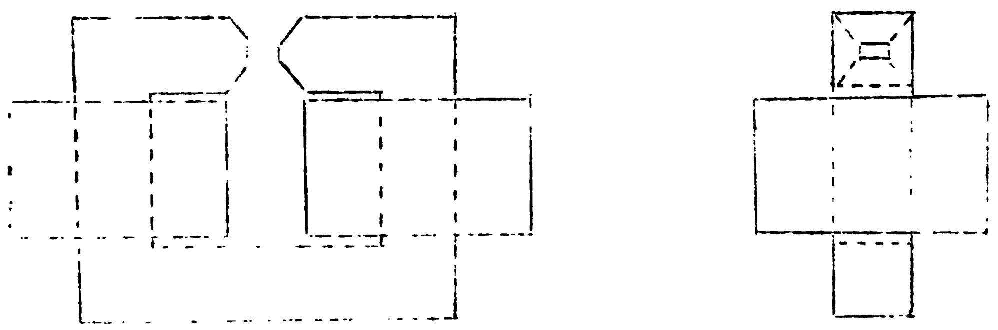
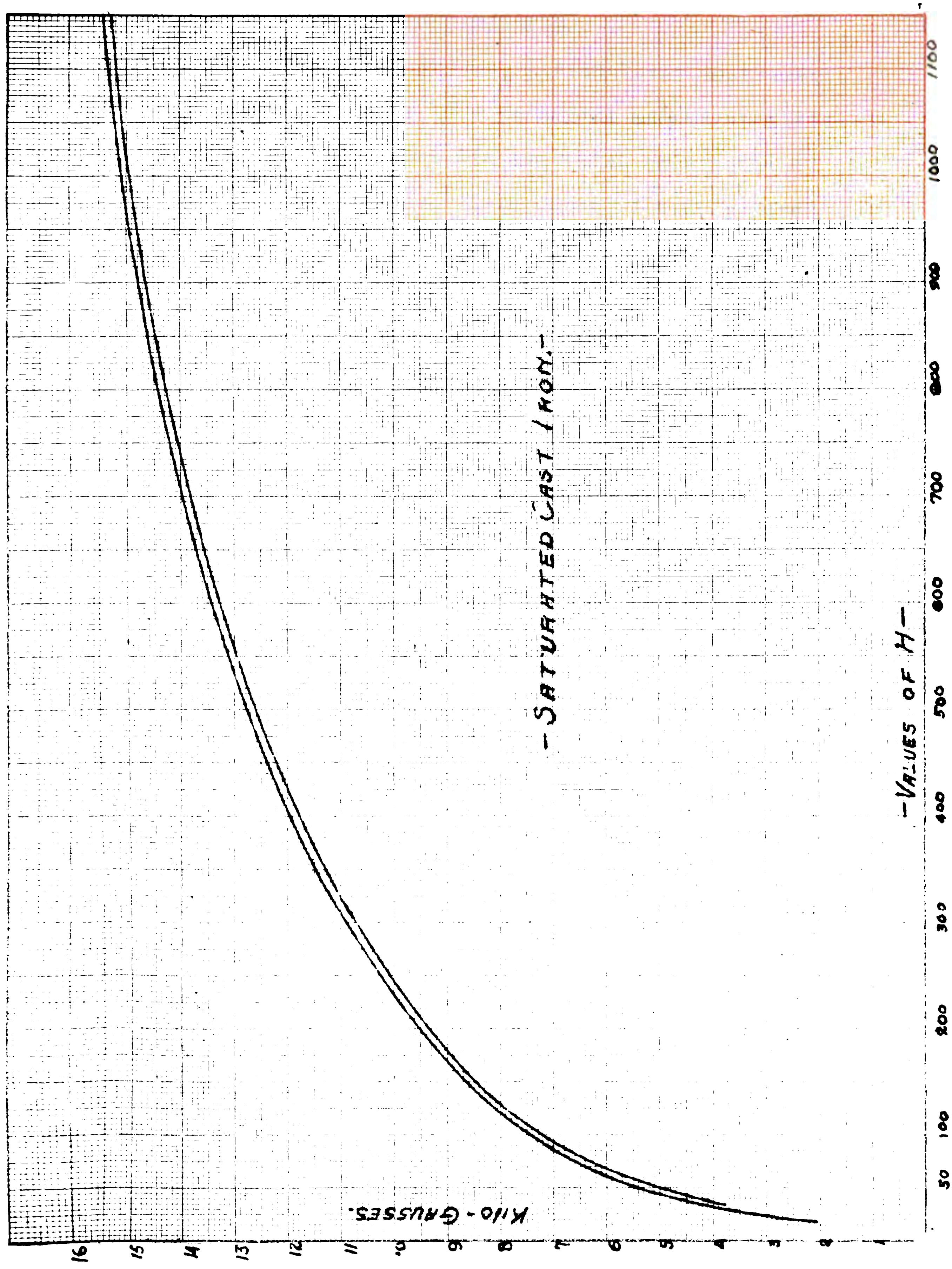


Fig. 27.

At the side of the iron specimen was placed a rectangular piece of hard wood of similar dimensions. Secondary coils of fine wire were placed about the iron specimen and the wooden bar.

The method of testing was as follows. The exciting current was brought to the desired value, and with the secondary coil on the specimen connected to a ballistic galvanometer, a number of readings were taken as the exciting current was reversed. By means of a double throw switch, the secondary turns on the wooden piece were now connected to the galvanometer, and with the current value the same as before, a second series of readings were taken. The current was increased to the desired value and the operation repeated.

The galvanometer was standardized as in the case of the ordinary permeability test, and the densities in the iron


-Saturated Cast Iron.-
Kilo-Gausses.
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PERMANENT MAGNETS.

In some classes of apparatus, particularly instruments, permanent magnets are used. The permanent magnet as distinguished from an electromagnet, is one which on account of its high retentivity, possesses a field of considerable strength after the initial magnetizing force has been removed.

The best permanent magnets are made of a high grade of crucible steel which contains a small percentage of some element which renders the metal extremely hard on being tempered, such as tungsten, vanadium, etc. After being properly shaped, the steel is heated to the proper temperature and suddenly cooled, making it very hard and glass-like. Such a metal gives a rather low permeability curve and a very large hysteresis loop.

Serviceable permanent magnets for certain uses may be made from cast iron which has been properly hardened. To harden a casting for this purpose, it should be heated up to white heat and chilled by immersing in water. This temperature should not be carried too high the first time or the casting will be likely to crumble. The first chilling will form a strong layer of metal on the outside which will permit of a subsequent heating to a higher temperature. The casting should now be reheated uniformly to a temperature just below the melting point and chilled again by immersing in running water or in ice water. Soft gray iron castings hardened in this manner show a fairly high residual magnetism and a good retentivity.

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ELECTRICAL CONDUCTORS.

Copper is almost universally used for making the conductors of electrical apparatus, unless it be that a high resistance is desired, as in the case of rheostats, heaters, etc. It is used in the form of round and square wires, and for larger machines, conductors are made of bars and strips.

Copper wire is made in certain standard sizes, drawn accurately to gauge. The wire most common in America is that drawn to the Brown and Sharp gauge, the sizes of which follow a definite law. The diameter is expressed in thousanths of an inch or mils, and the areas are expressed in circular mils (m), which for a given size of wire is the square of the diameter expressed in mils. The area may also be expressed in square mils |m| which is the true area expressed in thousanths of an inch or is D^2 x .7854. It will be seen that the circular mils, while not expressing the true area of cross section of the wires, are directly proportional to those areas, and most wire tables give both square and circular mils. The number of circular mils in a rectangular area may be found by reducing the area to square mils and dividing by .7854, thus:

$$\text{Circular mils} = \frac{\text{Area x } (1000)^2}{.7854} \qquad (9)$$

It will be convenient to remember that the circular mil is to the square mil as the circle is to the square in which it is inscribed, and that the number of circular mils in a section is therefore greater than the number of square mils. On pages 46 and 47 will be found tables which give the number

TABLE I.

GAUGE	BROWN & SHARPE GAUGE.	Diameter.				BIRMINGHAM GAUGE.	Diameter.			
NO.	(m)	BARE	SCC	DCC	TCC	(m)	BARE	SCC	DCC	TCC
0000	211,600	.460			.480	206,111	.454			.474
000	167,805	.410			.430	180,625	.425			.445
00	133,079	.365			.385	144,400	.380			.400
0	105,534	.325			.343	115,600	.340			.358
1	83,654	.289		.303	.307	90,000	.300			.318
2	66,373	.258		.272	.276	80,656	.284		.298	.302
3	52,634	.229		.243	.247	67,081	.259		.273	.277
4	41,743	.204		.216	.220	56,644	.238		.252	.256
5	33,102	.182		.194	.198	48,400	.220		.234	.238
6	26,250	.162		.174	.178	41,209	.203		.215	.219
7	20,820	.144		.156	.160	32,400	.180		.192	.196
8	16,510	.128		.140	.144	27,225	.165		.177	.181
9	13,092	.114		.126	.130	21,904	.148		.160	.164
10	10,384	.102	.108	.112	.116	17,956	.134		.146	.150
11	8,234	.0907	.097	.101	.105	14,400	.120		.132	.136
12	6,530	.0808	.087	.091	.095	11,831	.109		.119	.124
13	5,179	.0720	.078	.082	.086	9,025	.095	.101	.105	.109
14	4,107	.0641	.071	.075	.078	6,889	.0836	.089	.093	.097
15	5,257	.0571	.063	.068	.071	5,184	.072	.078	.082	.086
16	2,585	.0508	.055	.059	.063	4,225	.065	.071	.075	.079
17	2,048	.0453	.049	.053	.057	3,364	.058	.063	.068	.072
18	1,624	.0403	.044	.048	.052	2,401	.049	.054	.057	.061
19	1,288	.0358	.039	.044	.047	1,764	.042	.047	.050	.054
20	1,022	.0320	.036	.040	.044	1,225	.035	.039	.043	.046
21	810	.0285	.032	.036	.040	1,024	.032	.036	.040	.044
22	643	.0253	.029	.033	.037	784	.028	.032	.036	.040
23	510	.0226	.027	.031	.035	625	.025	.029	.053	.037
24	404.	.0201	.024	.028	.032	484	.022	.026	.030	.034
25	320.4	.0179	.022	.026	.030	400	.020	.024	.028	.032
26	254.1	.0159	.020	.024		324	.018	.022	.026	.030
27	201.5	.0142	.018	.022		256	.016	.020	.024	
28	159.8	.0126	.017	.021		196	.014	.018	.022	
29	126.7	.0118	.015	.020		169	.013	.017	.021	
30	100.5	.0100	.014	.018		144	.012	.016	.020	
31	79.70	.00893	.0125			100	.010	.014	.018	
32	63.20	.00795	.0115			81	.009	.0125		
33	50.13	.00708	.0105			64	.008	.0115		
34	39.75	.00631	.0098			49	.007	.0100		
35	31.53	.00562	.0086			25	.005	.008	.01	
36	25.00	.00500	.0080	.011		16	.004	.007		
37	19.83	.00445	.0075							
38	15.72	.00397								
39	12.47	.00353								
40	9.888	.00315								

TABLE II.

	BROWN & SHARPE GAUGE			BIRMINGHAM GAUGE		
Gauge No.	Lbs. per 1000 ft.	Feet Per Lb.	Ohms per 1000 ft.	Lbs. per 1000 ft.	Feet Per lb.	Ohms per 1000 ft.
0000	640.4	1.56	.0547	623.9	1.60	.0561
000	507.9	1.97	.0689	534.2	1.83	.0801
00	402.8	2.49	.0869	437.1	2.29	.0801
0	319.4	3.13	.1096	349.9	2.86	.1001
1	253.3	3.95	.1383	272.4	3.67	.1285
2	200.9	4.99	.1743	244.1	4.10	.1434
3	159.3	6.29	.2198	203.1	4.93	.1724
4	126.3	7.93	.2771	171.5	5.83	.2042
5	100.2	10.00	.3495	14655	6.83	.2390
6	79.45	12.61	.4406	124.7	8.02	.2807
7	63.01	15.90	.5556	98.06	10.2	.3570
8	49.97	20.05	.7007	82.41	12.1	.4249
9	39.63	25.28	.8835	66.30	15.1	.5281
1C	31.42	31.38	1.114	54.35	18.4	.6442
11	24.92	40.20	1.405	43.58	22.9	.8033
12	19.76	50.69	1.771	35.96	27.8	.9736
13	15.70	63.91	2.234	27.32	36.6	1.282
14	12.43	80.59	2.817	20.85	48.0	1.679
15	9.857	101.63	3.552	15.69	63.7	2.231
16	7.817	128.14	4.479	12.79	78.2	2.738
17	6.199	161.59	5.648	10.18	98.2	3.439
18	4.916	203.76	7.122	7.268	138.	4.818
19	3.889	264.26	8.980	5.340	107.	6.558
20	3.092	324.00	11.32	3.708	270.	9 443
21	2.452	408.56	14.28	3.099	323.	11 30
22	1.944	515.15	18.01	2.373	421.	14 75
23	1.542	649.66	22.71	1.892	529.	18.51
24	1.225	819.21	28.63	1.465	683.	23.90
25	.9699	1032.96	36.10	1.221	826.	28.92
26	.7692	1302.61	45.52	.9808	1020.	35.70
27	.6100	1642.55	57.4C	.7749	1290.	45.19
28	.4837	2071.22	72.39	.5933	1690.	59.02
29	.3836	2611.82	91.28	.5116	1960.	68.45
30	.3042	3293.97	115.1	.4339	2290.	80.33
31	.2413	4152.22	145.1	.3027	3300.	115.7
32	.1913	5236.66	183.0	.2452	4080.	142.8
33	.1517	6602.71	230.8	.1937	5160.	180.7
4	.1203	8328.30	291.0	.1483	6740.	236.1
5	.0954	10501.35	366.9	.0757	13200.	462.7
6	.0757	13238.83	462.7	.0484	20700.	723.0
7	.0600	16691.06	583.5			
8	.0476	20834.65	735.7			
9	.0377	26302.23	927.7			
0	.0299	33175.94	1170.0			

of circular mils for the different sizes of wire.

The wire table for the B. & S. gauge has a few simple relations, which will enable one, if a few constants are caried in the memory, to construct the whole table mentally with approximate accuracy.[*]

A wire which is three sizes larger than another wire has twice the weight and half the resistance, or a wire which is ten times larger than another has ten times the weight, and one tenth the resistance.

No. 10 wire is approximately .10 inches in diameter, has an area of approximately 10,000 circular mils; a resistance of approximately one ohm per thousand feet at 20 degrees Centigrade and weighs approximately 32 lbs. per thousand feet.

The weight of a thousand feet of No. 5 wire is 100 lbs. The relative values of resistance for decreasing sizes and of weight and area for increasing sizes for consecutive sizes are:

.50 .63 .80 1.00 1.25 1.60 2.

The relative values of diameters of alternating sizes of wire are,

.50 .63 .80 1.00 1.25 1.60 2.

Conductors of large size are usually specified in circular mils. As No. 10 wire has approximately 10,000 circular mils, and a resistance of one ohm per thousand feet, and as the length of a wire which has a given resistance is proportional to its area, it follows, therefore, that the length in feet of a copper conductor having a resistance of one ohm may be found by dropping one cipher from the number expressing its circular

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[*] How to Remember the Wire Table, Chas. F. Scott, Elec. Club Journal, April, 1905.

Mils. For example; No. 10 wire has 10,000 circular mils and a resistance of one ohm per thousand feet; a 300,000 circular mil conductor has a resistance of one ohm per 30,000 feet, and a 1,000,000 circular mil conductor has a resistance of one ohm per 100,000 feet. The weight of a given length is proportional to the area, therefore, the weight of a conductor having, say 50,000 circular mils is greater than that of No. 10 wire in the same ratio that its area is greater. 500,000 circular mils has 50 times that of No. 10 wire, or axapproximately 50 times 32 lbs, which equals 1600 lbs per thousand feet. In this way the approximate characteristics of copper conductors of all sizes may be quickly ascertained.

To find the resistance, drop one cipher from the number of circular mills: the result is the number of feet per ohm.

To find the weight, drop ciphers from the number of circular mil. and multiply by the weight of No. 10 wire.

Most of the wires used in the construction of electrical machinery are insulated with cotton covering laid smoothly on the conductors. This covering may be obtained either single, double, or triple thickness. Again, the thickness of a single covering depends upon the size of the wire. In the tables will be found the bare diameter of the wires, as well as the diameters with single, double and triple cotton covering. It should be understood that this varies somewhat with different manufacturers but in general the following table of diameters will hold.

TABLE III.

THICKNESS OF COTTON COVERING ON STANDARD WIRES.

Double Cotton Covering, (Fine)

All sizes to No. 20, add	6 mils.
Nos. 19 and 18, add	8 mils.
Nos. 12 and larger, add	12 mils.

Double Cotton Covering. (Ordinary)

All sizes to 18, add	10 mils.
Nos. 17 to 13, add	12 mils.
Nos. 12 and larger, add	14 mils.

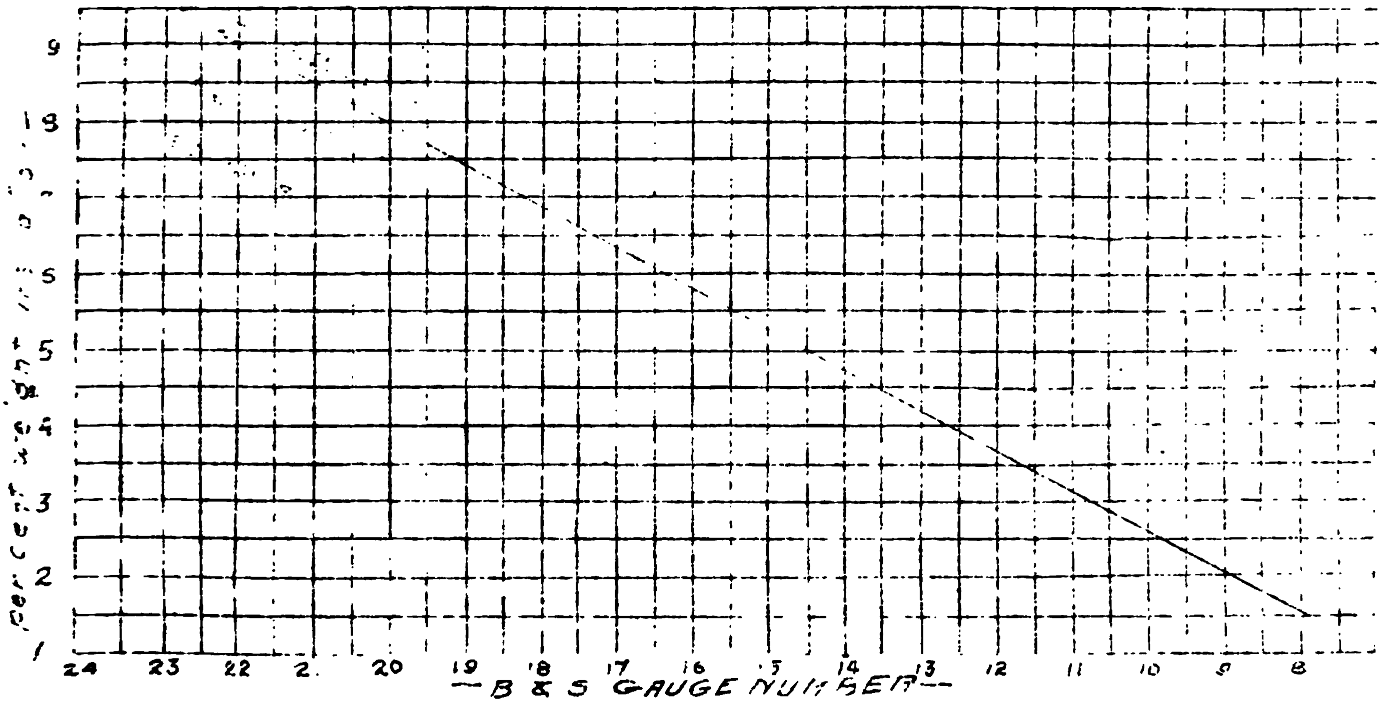


Fig. 28.

In Fig. 28 is a curve showing the percentage by which average commercial double cotton covering increases the weight of cotton covered magnet wire. This increase in weight is important, since the weight stated by the designer is likely to be derived from standard wire tables and refers to the copper alone. The curve will serve as a good basis for estimating

the weights of the insulated wire, which is always sold by the pound.

The number of round wires which will wind in a given area may be found from the equation:

$$n = \frac{A}{(d + 2t)^2} \qquad (10)$$

where:-
n = number wires per sq. inch.
A = winding area in sq. inches.
d = bare diameter of wire in inches
t = single thickness of insulation in inches.

The Mattiessen Standard of Resistance, as adopted by the American Institute of Electrical Engineers and as indicated in Fig. 29 shows the increase in resistance of one mil foot of

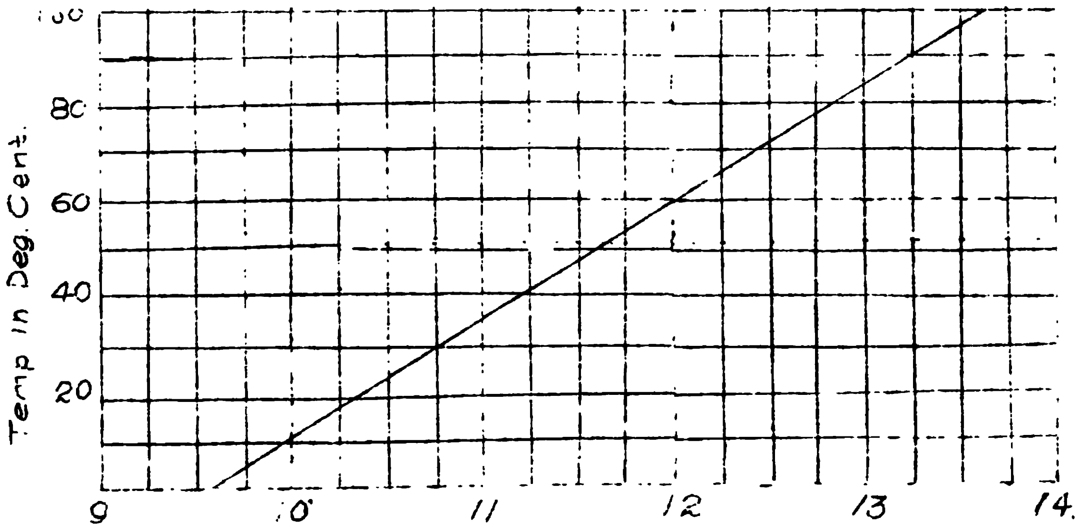


Fig 29 Ohms per mil foot.

—pure copper as the temperature is increased. Since the resistance is directly proportional to the length and inversely proportional to the cross section, if K have the resistance of one mil foot, we can calculate the resistance of any size of wire of any length and at any temperature from the equation:

$$R = \frac{K \times L}{\quad} \qquad (11)$$

Where,

K = the ohms per mil foot at the given temperature,

L = the length of the wire in feet

(m) = the number of circular mils corresponding to the size of wire considered.

Also from equation 11 we have for the length of a wire to give a required resistance,

$$L = \frac{R \times (m)}{K} \qquad (12)$$

or further, from Ohm's Law,

$$R = \frac{E}{I} \qquad (13)$$

which substituted in equation 12 and reduced gives

$$(m) = \frac{K \times L \times I}{E} \qquad (14)$$

which determines the size of wire which must be used when the temperature, length of wire, current flowing and difference of potential at the ends of the wire are known.

If the difference of potential at the terminals is to be found, then from equation 14,

$$E = \frac{K \times L \times I}{(m)} \qquad (15)$$

which is a convenient expression to use.

Wires of iron, German silver, and other alloys may also be obtained where their use is desirable, and in the tables on page 53 will be found a table giving the resistances of German silver and iron conductors. It will be well to remember that the resistance of ordinary German silver wire is about thirteen times that of copper, that the percentage increase in resistance of German silver wire for a given increase in temperature is less than that of copper, while the percentage

of increase of resistance in the case of iron is greater than that of copper.

TABLE OF GERMAN SILVER AND IRON WIRE.

Gauge Number. B&S	W&M	Ohms per 1000 feet. German Silver, 18 per cent.	Iron	Ohms Per Pound	Pounds per 1000 feet.
	12		6.06		29.2
10		18.72		.59652	
	16		7.29		27.5
11		23.598		.94842	
12		29.754		1.50786	
	14		10.41		24.0
	15		12.09		22.4
13		37.512		2.39778	
14		47.304		3.8124	
	16		15.15		21.8
15		59.652		6.0624	
	17		20.01		18.3
16		75.222		9.639	
	18		28.4		17.6
17		94.842		15.327	
	19		39.0		16.9
18		119.61		24.3702	
19		155.106		40.9896	
	20		52.0		13.8
	21		62.0		13.7
20		190.188		61.614	
2.		239.814		97.974	
	22		82.0		11.2
22		302.382		155.772	
	23		102.		10.9
	24		118		10.5
23		381.33		247.734	
24		480.834		393.93	
	25		159.		8.9
	26		196		8.6
25		606.312		626.31	
	27		216.		7.7
	28		248		6.9
26		764.586		995.958	
27		964.134		1583.622	
28		1215.756		2518.075	
29		1533.06		4004.082	
30		1933.038		6368.356	
31		2437.236		10119.978	
32		3073.77		16096.356	
33		3875.616		25589.628	
34		4888.494		40712.76	
35		6163.974		64729.87	
36		7770.816		102876.482	
37		9797.166		163524.78	
38		12357.198		257764.68	
39		15570.828		409546.8	
40		19653.57		652024.62	

Wires of square and rectangular cross section may be obtained and used where a minimum of space is essential.

INSULATION AND INSULATING MATERIALS.

One of the most important and perhaps the least understood of all the elements entering into the construction of electrical machinery is the insulation. The continuity of operation and the life of the machine depend largely upon the care and judgment exercised in the selection and use of insulating materials.

The most important requisites of an insulating material, are,

1st, High insulating quality,

2nd, Ability to withstand heat,

3rd, Ability to withstand mechanical strains and vibration, flexibility and freedom from brittleness.

4th, Durability,

5th, Freedom from the deleterious effects of oil and moisture.

6th, Adaptability.

The properties of insulating materials have been classified as follows:*

1. Electrical properties.

   a. Insulation resistance of conductivity expressed in ohms per cubic centimeter.
   b. Disruptive or dielectric strength, measured by the high potential voltage necessary to puncture the material.
   c. Dielectric constant or specific inductive capacity measured by the capacity in microfarads of a condenser having the particular material, as dielectric separating the metal plates.

2. Mechanical Properties.

   a. Strength and workability (For solids)
   b. Flexibility and workability (For semi solids)
   c. Viscosity (For liquids)

*Max von Recklinehausen, Amer. Chem. Society, ArApril 16, 1903.

3. Chemical Properties.

   a. Combustibility.
   b. Property of resisting the influence of moisture, air, acids, etc. (Hygroscopic quality)

The desirable qualities are mainly good insulation resistance, high disruptive strength, fair mechanical properties, especially workability. Undesirable qualities are mainly combustibility and changes in the electrical, mechanical properties with rise of temperature or with age.

In the various types of electrical apparatus, many kinds of insulation are used, the most common of these being mica, paper, cotton cloth, silk, cotton and silk treated with oil or varnish, fibre, oil, hard rubber, porcelain and special preparations such as Vulcabeston, Megchmit, Ambroin, Psychiloid, Isolit, Litholite, Adit, Lava, Celluloid, etc.

The insulating material which should be used in the different parts of a machine will depend to some degree upon the class of machine, voltage and the method of construction. It will therefore be best to consider the various classes of insulating materials and their applications to the different forms of machines.

FIBROUS INSULATING MATERIALS.

Paper and other materials of like texture are largely used in the construction of electrical machinery, owing to their close texture, cheapness and flexibility. Manilla, express and bond paper show a high disruptive strength, and are largely used. Red rope paper, which is tough and softer, is often used for armature slots. The insulating quality of all insulating papers is improved by coating with varnish.

Alternate layers of thin sheets of mica and paper also give an insulator of fair mechanical strength and high insulation. Whenever used for insulating purposes, paper should be impregnated with good moisture proof insulating varnish which will make it water proof and also add to its insulating properties.

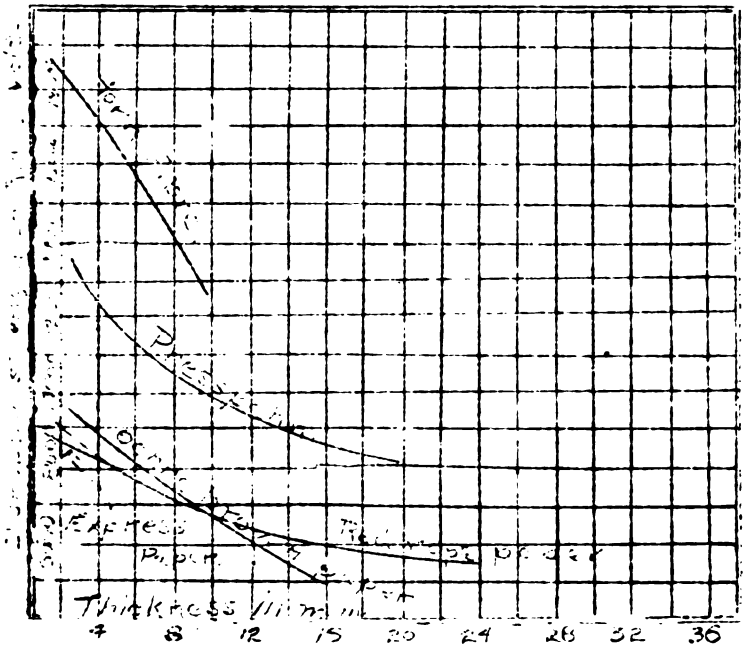


Fig. 29.

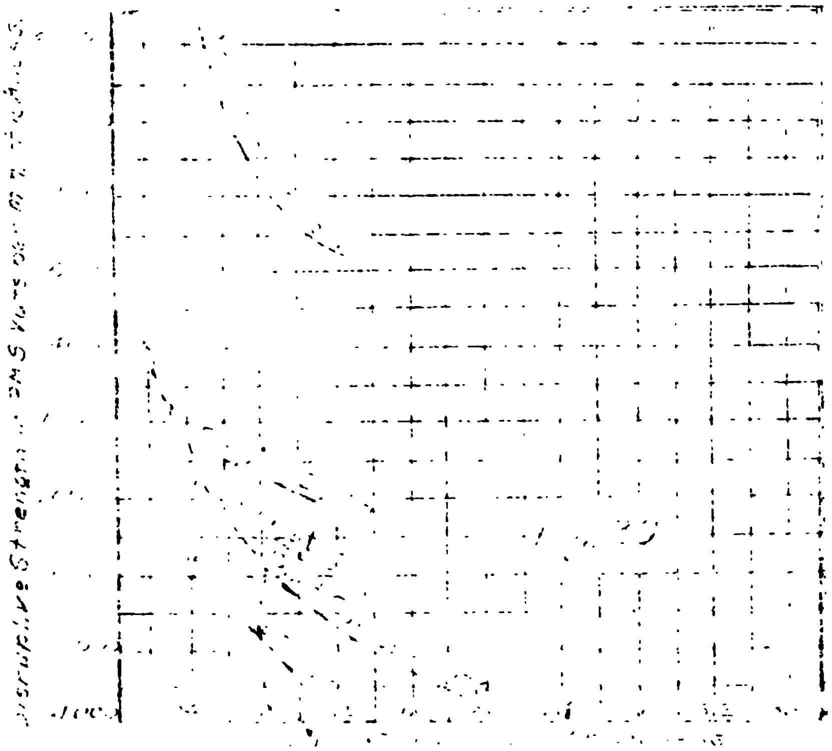
In Figs. 29 and 30 will be found curves showing the disruptive strength of different qualities of insulating paper of various thicknesses.

INSULATING CLOTH AND FABRICS.

On account of their mechanical strength and the ease and uniformity with which they may be applied, large quantities of insulating cloth and fabric are used in the sconstruction of all classes of electrical machinery. In general, the insulating strength does not lie in the fabric itself, but rather in the insulating material with which it is impregnated.

Empire cloth, which is cambric treated with linseed oil, varnished cambric, oiled linen, oiled canvas, and oiled silk are all largely used. The insulating compounds are in some

cases applied ato the cloth before it is used, and oftener after the fabric has been placed upon the apparatus. The insulating strength of various fabrics will be found in Fig.30



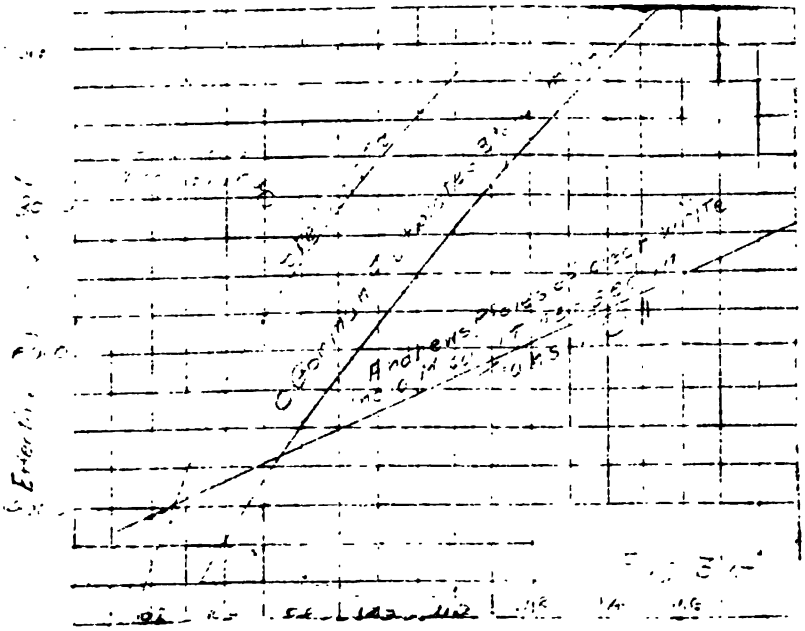
MICA.

Mica, which is one of the best known dielectrics, is in its natural state a good insulator. Unfortunately, it is difficult to make into required shapes or forms. In the natural state, the mica is in thin sheets, in which form it can be used for some purposes. Its ability to withstand high temperatures without deterioration is a point in its advantage. The insulating quality of mica varies considerably. White and amber mica are best for electrical purposes.

In order to render the mica more flexible, and to adapt it to the process of forming, various compounds of mica are made, such as Micanite, Megchmit, and Megotalc.

Micanite consists of mica separated into very thin sheets, subsequently cemented together while hot and under high pressure

When heated it may be pressed into suitable forms.



The ordinary shellac is sometimes used for sticking sheets of mica together, but it is inferior to the cement used in the manufacture of the best grades of Micanite. Micanite is used in the insulation of commutators, high tension transformers and in the slots of high voltage machines.

Megohmit is made by very much the same process as Micanite, except that the percent. of cement used is less. It can also be formed while heated.

Mica cloth and mica paper are commercially sold, and consist of layers of flexible sheets of mica covered with layers of linen or paper.

TABLE IV.

DISRUPTIVE STRENGTH OF MICA COMPOUNDS.

MEGOHMIT.			MICANITE	
Thick. in In.	Ins.Str. in Volts	Ins.Str. .001 In.	Material.	V.per.001" when cold.
0.0063	8,000	820	Micanite plate,	1020
0.0102	12,500	795	Flexible micanite plate	760
0.0152	20,500	870	Micanite cloth,	430
0.0203	2[illegible],500	872	Micanite paper,	455
0.0254	36,000	915		

Megotalc is composed of thin sheets of mica cemented together with a thin layer of shellac. It is made in the form of plates, cloth and paper.

Micanite, Megohmit and Megotalc can be pressed into form for insulation of slots and for field spools. For bushings, brush holder appliances, collector ring insulation, field spools, etc, insulators made of molded compounds are now largely used. The manufacture of the different compounds used are secrets. Some of these, of which Ambroin is a typo, are composed of fossil copal and silicates. Some of the forms of Ambroin may be machined and polished, and in the process of manufacture, the material can be pressed into almost any desired shape: In a paper read before the Student Section of the Institution of Electrical Engineers, Simmons states that Psychloid, which has a high insulating strength, is made from a base of paper pulp, which is dried and then put through a secret chemical process. It is impervious to the effects of moisture and acids, and can be moulded into any desired shape.

FIBRE.

Vulcanized fibre is produced by treating specially prepared vegatable fibre with powerful chemical agents and subjecting to heavy pressure. It possesses great mechanical strength, and is insoluable in ordinary solvents. It absorbs water very much as does wood, and can be obtained in the form of sheets, rods and tubes. It can be worked in a lathe, drilled, sawed and punched, and will take a fine polish. Unlike Ambroin and other compounds, it can not be moulded during the process of manufacture.

TABLE V.

EMPIRE CLOTH.*
Linseed Oil Treatment.

Material	Thickness in mils	Breakdown voltage	Volts per mil.
Muslin,	5	5,800	1,730
Irish Linen	6	8,600	1,433
Muslin,	7	7,800	1,114
Muslin,	8	5,000	625
Muslin,	10	7,400	1,036
Muslin,	12	12,430	1,036
Muslin,	15	15,980	1,065
Canvas,	16	7,850	491
Manila Rope Paper,	5	6,700	1,340
Bond paper,	5	8,500	1,700

TABLE VI.

MICANITE INSULATORS*

Material	Thickness in mils	Volts per mil	Million meg-ohms per cu. in.
Extra Flexible Micanite paper,	7	325	503
Micanite paper,	8	407	
Micanite cloth,	11	439	
Flexible Micanite Plate,	10	755	30° C 320 100° C 268
Micanite Plate No. 1,		1,012	

TABLE VII.

CHAMPION MICA BOND INSULATORS*

Material	Thickness in mils	Volts per mil
Flexible Mica Bond,	8	755
Mica Bond Cloth	11	435
Mica Bond paper,	8	400
Mica Bond Plate No.101		1,012

Champion Insulating Cloths and Papers.

Asbestos paper #1.	9	320
Special Rope Paper,	7.5	936
Rope paper No. 1.	4.5	936
Bond paper	4	939
Express paper,	8	930
Muslin # 1.	7	654
Muslinl Special,	5	660
Canvas	12.5	650
Linen	6	596

* Given by Manufacturers

INSULATING VARNISH.

To improve the insulating qualities of fibrous materials, they are usually impregnated with some form of insulating varnish eof either the baking or air drying variety. For most purposes, an insulating varnish should give a permanent and uniform coating of insulation which is tough, which will not be influenced by heat, and which will not deteriorate with age. It should also be free from the effects of acids, moisture and oil. Ordinary gum shellac, dissolved in alchohol, with which many of the earlier machines were insulated, is no longer used, owing to its rapid deterioration under the effects of heat and mechanical vibration. A good baking insulating varnish should give a breakdown test of between 1200 and 1800 volts per .001 inch. Most of the varnishes on the market are compounds [illegible] of linseed oil, turpentine and resin, and are usually applied by dipping, after which the coil is baked at a temperature of from 60 to 80 degrees Centigrade.

Armalac is black parafin dissolved in naptha. In appearance, it resembles asphaltum paint. It dries tough and requires very little baking.

TABLE VIII.

CLOTH AND PAPER COATED WITH STERLING VARNISH.*

Material	Varnish	Thickness mils	Breakdown voltage	Volts per mil	Meg-ohms per sq. in.
Muslin	G.P.Ins.	10.5	7,300	695	190.836
"	Qk.Dry.G.P.Ins.	9.	6,600	733	47.730
"	Spec.Cloth Varn	6.2	5,600	854	37.700
""	Bakg.Voltalac	8.5	9,000	1358	2948.635
"	Air Dry.Voltalac	7.8	5,480	703	28.407
Paper	G.P.Ins.Varn.	5.5	5,800	1054	153.027
"	Qk.Dry.Ins.Varn.	4.8	4,300	895	95.472
"	Bakg.Voltalac	5.	5,160	1032	7500.000
"	Voltalac	8.	6,300	787	126.360
"	Ex.Blk.Coil Varn.	6.5	6,300	969	64.000

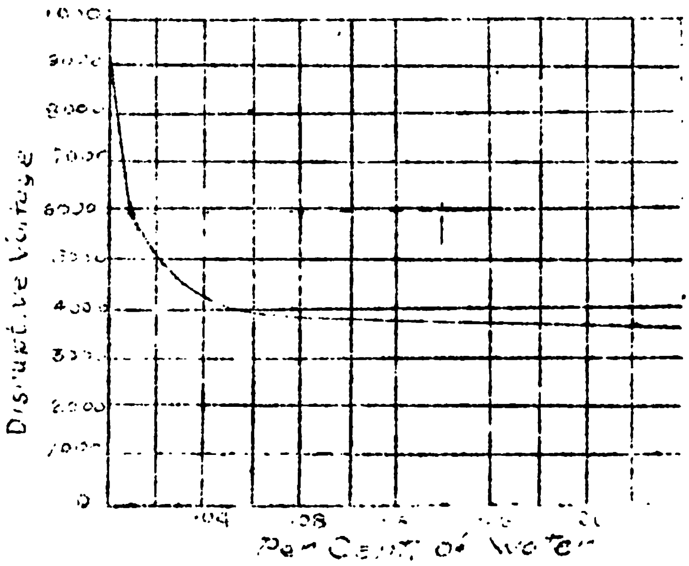
*Data furnished by manufacturers

In baking varnished coils, care should be taken to not heat to too high a temperature. The varnish will be more readily absorbed if the coil is heated prior to dipping.

It is the practice of some companies to apply the insulating compounds to coils of higher voltage machines by heating them in a vacuum. This not only extracts the moisture from the pores, but the air as well. When this process has been carried out, the insulating compound is admitted into the vat under pressure and at fairly high temparature. Coils insulated in this manner, especially those where the winding is of considerable depth, show high insulation.

OILS.

Oil is used for insulation in transformers. The oil used for this purpose is a high grade of mineral oil, which should be free from moisture, have high flashing test of not less than 180° C. Burning test should not be less than 200° C., and be free from impurities. The disruptive strength of oil is lowered by the presence of water or moisture



The presence of water may be detected by drawing oil from the bottom of the containing vessel. Moisture is present if a hissing noise is produced when a hot iron is thrust into the oil. Moisture may be removed by heating the oil for some time at or near the boiling point of water. The following table will indicate the improvement made in the insulating strength of oil by drying it thoroughly.

	Kilovolts.	
Distance	Before Boiling	After Boiling.
10 mm.	50	105
18 mm.	78	170
24 mm.	88	184

Like other insulating materials, the disruptive strength of oil does not increase directly with the thickness of the layer. In the following tables will be found the results of tests on a number of commercial insulating oils.

TABLE X.
SAMPLE OF OIL FROM STANDARD OIL CO., BAYONNE, N.J.

Sample	Distance	Kilovolts.
# 1	3 mm.	48
# 1	6 mm.	70
# 1	10 mm.	100
# 2	3 mm.	59
# 2	6 mm.	75
# 2	10 mm.	99
# 3	3 mm.	54
# 3	6 mm.	80
# 3	10 mm.	97

TABLE XI.
OILS FROM VACUUM OIL CO. ROCHESTER, N.Y.
All oils treated for transformer use.

			Deg. F.		
Sample	Gravity	Cold	Flash	Fire	Viscosity 110-170
1	26.5	40	485	545	120
2	30.3	0	380	430	130
3	31.0	25	360	410	132
4	32.0	15	340	390	74
5	34.0	15	320	360	54
6	39.0	20	265	305	35

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Sample	Distance	Kilovolts by Sec. Voltmeter	Kilovolts by Ratio
1	3	51	48
"	6	71	67
"	10	114	95
2	3	43.5	41.8
"	6	59.4	56
"	10	69.5	65
3	3	47	35
"	6	71	65
"	10	101	92
"	14	101	92
4	3	51	46
"	6	89	84
"	10	91	88
"	14	117	106
"	18	137	128
5	3	52.5	48
"	6	56	52
"	10	59	54
"	,14	66	60
6	2	52.5	48
"	3	38	35
"	66	72	68
"	10	93.5	89
"	14	142.	135
"	2	45.5	38
"	3	66	60
"	4	75	72
"	8	114.5	95

6 is 300 deg. Mineral Seal.

PART TWO

THE DESIGN OF ELECTROMAGNETS,
CLUTCHES AND BRAKES.

It is well known that when magnetic lines of force eminate from a magnet to the air, or pass from the air to the iron, a tension exists in the lines of force. The tension per unit are is proportional to the square of the intensity.

The first assumption usually made is that of the material to be used in the different parts of the magnetic density at which each part of the circuit is to be worked. Having assumed the value of B for a given part of the circuit, the value of H is determined from the curve, for use in equation 10; we can then place this assumed value of B, the density in the working air gap, in the expressions:

$$P = \frac{B^2 A}{8\pi} \text{ dynes,}$$

$$P = \frac{B^2}{8\pi} \text{ dynes} \qquad (10)$$

or the total pull may be expressed:

$$P = \frac{B^2 A}{8\pi \times 91 \times 455.6} \text{ in lbs.} \qquad (11)$$

$$\frac{B^2 A}{11,183,461} \text{ pounds pull.} \qquad (12)$$

where;
B is the magnetic density in gausses,
A is the area in sq.cm.
P is the pull in lbs.

From this equation, the pull or tractive effort which a magnet or given polar area is exerting may be calculated.

There are, however, many considerations of practical importance which materially effect the calculations of an electromagnet.

1st. The proportioning of the magnetic circuit to carry the required number of lines of force at an economical density for the material used in the circuit.

2nd. The selection of the proper material for the purpose considered, which involves the first cost of material and cost of shaping in the machine shop, together with the final cost of operating, or the efficiency of the completed mechanism.

3rd. The arrangement fof the various parts of the mechanism so that undesirable leakage will be reduced to a minimum.

4th. The design of the windings so as to secure economy in the first cost of copper, and small I^2R loss in the operation of the device.

5th. The insulation of the wire of the windings and the insulation of the windings themselves from the other parts of the mechanism.

6th. The correct mechanical design of the purely mechanical features of the device, so that it shall at the same time be able to endure the stresses applied to it in working, and present a correct and pleasing appearance to the eye. This last consideration of correct mechanical design is frequently lost sight of by designers of electrical apparatus and is a most serious defect when omitted.

These considerations can best be illustrated by considering definite cases. Suppose it is necessary to design an electro-magnet for some specified purpose. In general, such a magnet would have its iron circuit put up somewhat as follows.

The yoke will be of cast iron, if it be a magnet of considerable size, in which our values of B may range from 4,000 to 6,000 gausses, according to the quality of iron selected, which it will be seen by reference to the curves on pages 28 and 29, will correspond to values of H ranging from 5 to 40, beyond which limits, it is seldom advisable to go. For most work, values of H not far from 20 may be used to advantage. The cores C C, will be of soft wrought iron and let into holes in the yoke. They are made of wrought iron, as approximately three times the magnetic density can be employed that could be used for cast iron. Thus, for a given value of the total flux ϕ, about one third of the area of cross section is necessary, and the length of a turn of wire about the core is considerably reduced, making a corresponding reduction in the weight of copper possible.

The joint between the cores and the yoke should be as perfect as possible, which may be accomplished in several ways. The cores may be forced into position by hydraulic pressure; the yoke heated and shrunk on the cores, or what is a more common method, and for the most cases is perhaps the best construction, is as follows: The cores are turned to the same diameter as the holes in the yoke the yoke is split as indicated in Fig. 33, and clamped upon the body of the core means of bolts or screws. Whenever possible, the heads of such bolts or screws should not be allowed to project above the surface of the yoke, or considerable magnetic leakage is occasioned.

In the case of small magnets, such as are used for bells, annunciators, etc., the yoke is usually made of wrought iron

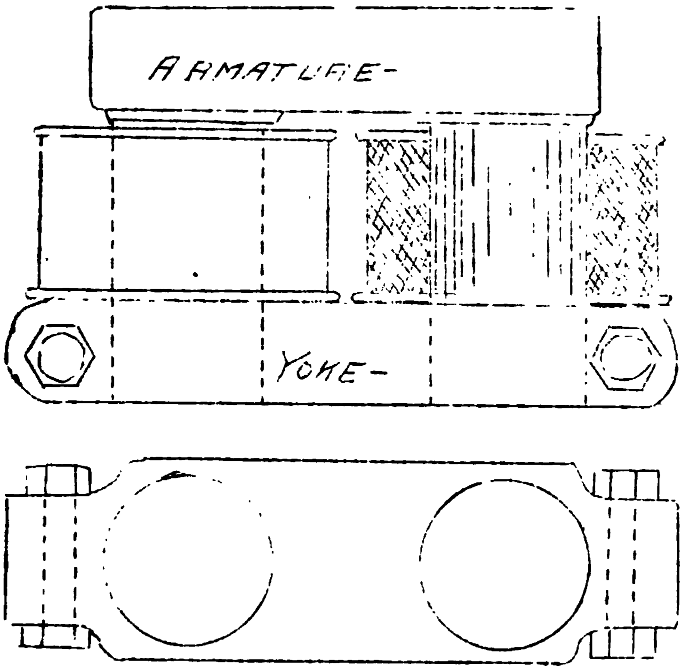


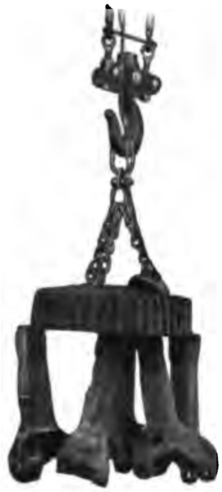
Fig. 33.

with the cores simply faced and secured to the surface of the yoke by means of screws, but this does not always provide a thoroughly satisfactory magnetic joint. A later and more approved method in the construction of small magnets is to pass the core through the yoke and then expand it by mechanical means.

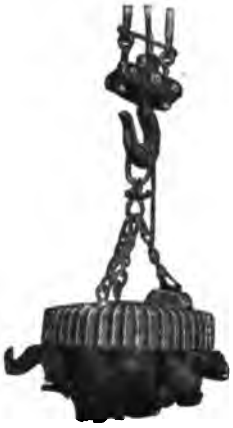
Where the construction will permit, it is often advisable to make the cores and yoke of one piece of wrought iron bent into the shape of a letter U, thus giving a continuous magnetic circuit without joints.

The armature is usually of wrought iron, carefully surfaced and should have between it and the poles a short air space, so that the residual magnetism of the circuit will not cause it to adhere to the poles after the magnetizing current has been removed. This air space is usually secured by placing small copper pins or screws in the air gap face of the core, which project slightly above the surface of the core, so that the armature, when attracted, does not come into direct contact with the poles, but rests upon the copper surface presented.

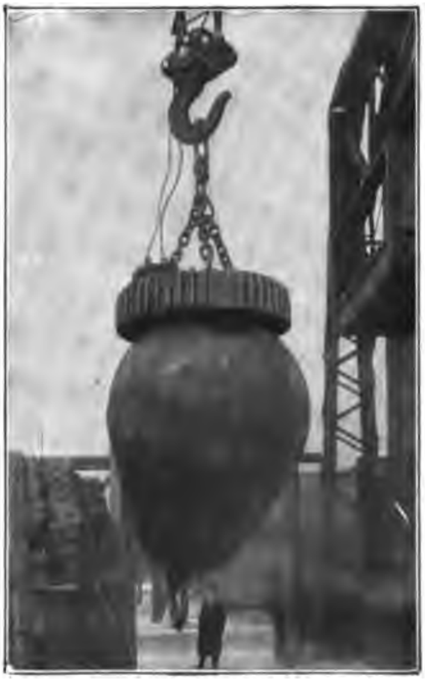
In the shaping of the magnetic circuit, care should be taken to arrange the parts so that all portions exhibiting opposite polarity will be removed from each other as far as possible, and at the same time observe the law, that the length



PIG MAGNET.



PIG MAGNET.



ELECTRO MAGNET.

ELECTRO-MAGNETIC APPARATUS, ELECTRIC CONTROLLER AND SUPPLY COMPANY.

of the magnetic circuit should be short, so that it may be magnetized with a minimum expenditure of energy in the windings.

All sharp angles should be avoided in the surface of the magnetic circuit and in general the radii of curvature of the surfaces of the magnetic circuit should be as great as possible.

The windings must be designated so that they will supply the required M.M.F., and at the same time have a resistance such that with the given E.M.F. available at the terminals of the winding, only the required current will flow through the wire.

There must be provided sufficient radiating surface on the coil so that the I^2R losses producing heat in the winding will not raise the temperature of the coil to a point where there is danger of burning the insulation of the winding. A rise in temperature above the surrounding air, under continuous working of from 30° to 50° Centigrade is safe, and to secure this result there should be provided from one and one-half to three sq. in. of radiating surface per watt radiated.

The following rule which is a modification of that given by Esson (See S.P.Thompson, Vol.1, page 374) shows this relation more closely.

$$T^{o}C = \frac{83\ W}{S} \qquad (13)$$

where;

W is the I^2R loss expressed in watts,
S is the radiating surface expressed in sq.in.
$T^{o}C$ is the rise in temperature above the air.

Equation 13 assumes a ratiation coefficient of $\frac{1}{83}$ = .012 watts per sq. in. per degree C. rise in temperature. This coefficient is based on Timmerman's results (See Trans. Amer.Inst.Elec.Engrs., p.342, Vol. X, 1893.) which are in part as follows.

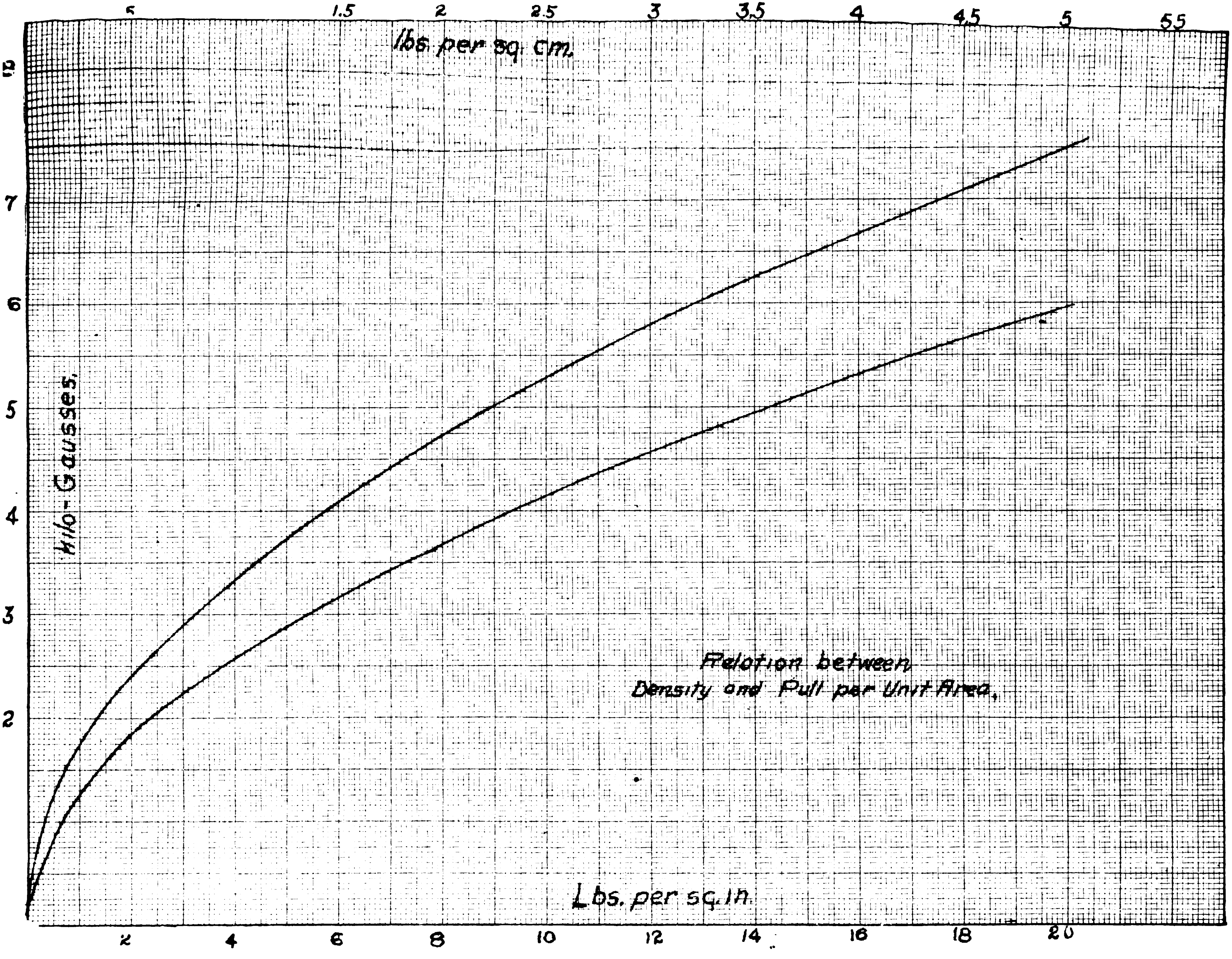
TABLE XII.

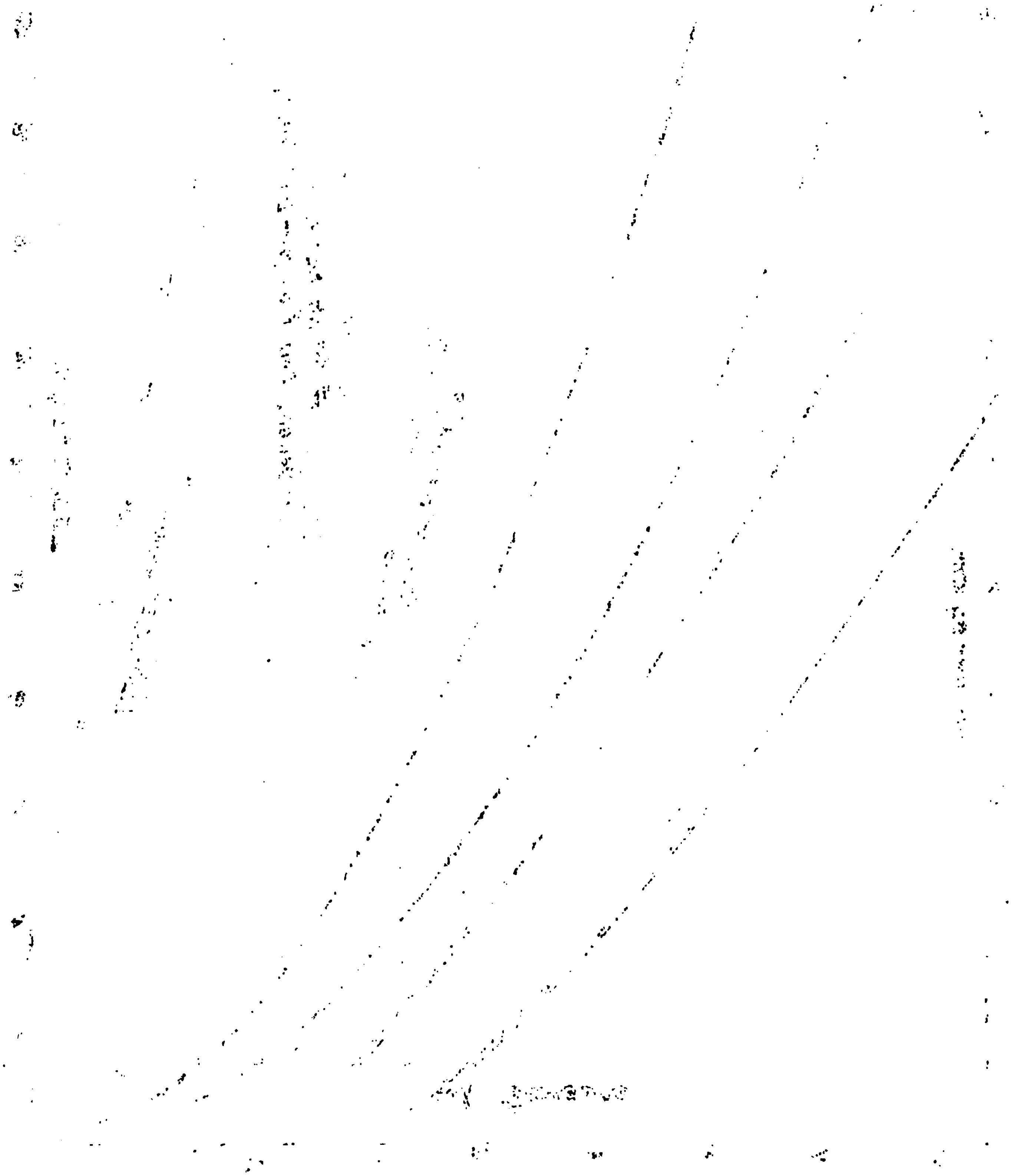
CYLINDER FREE.		100 % OF CYLINDER COVERED BY POLES. AMALL AIR GAP.	
Rise in Temperature degrees C.	Watts radiated per degree rise in temperature per per square inch.	Rise in Temperature degrees C.	Watts radiated per degree rise in temperature per square inch.
49	.01128	53	.01048
92	.01200	97	.01145
130	.01282	130	.01225

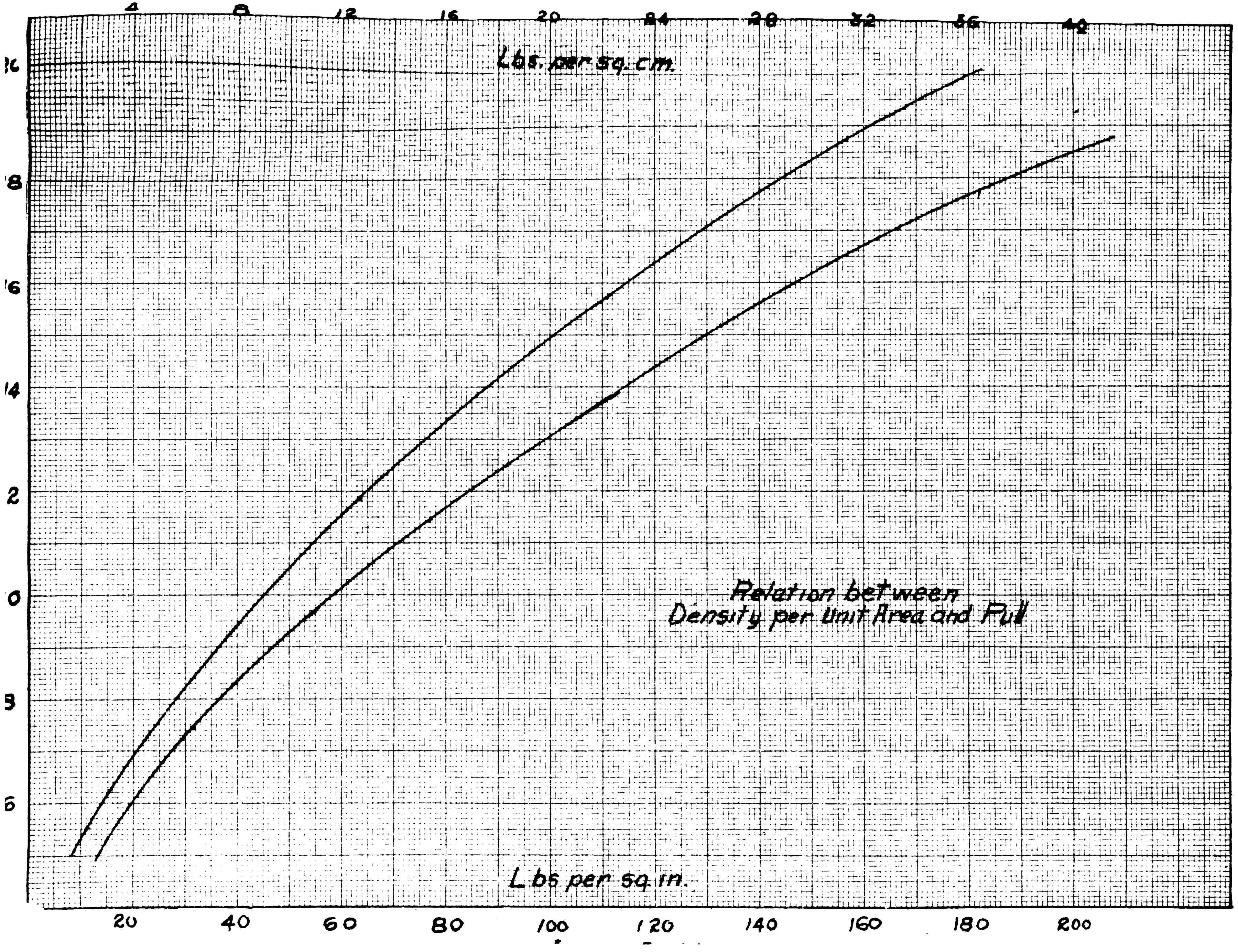
----oOo----

A tempreature as high as 100° C. above the surrounding air may be used without carbonizing the insulation if properly made, but it is desirable to operate at a lower temperature unless some important consideration actually demands this value which corresponds to a radiation of nearly two watts per sq.in.

In beginning the design of an electromagnet, having chosen the material of which it is to be made, the magnetic density at which it is to operate should be selected. The curves on pages 72 and 73, which are calculated on the assumption that the distribution of the flux from the polar surface is uniform, may be used to ascertain approximately the area of the poles, remembering that if the magnet is bi-polar, one half of the total pull will be exerted by each pole. It will now be well to lay off on the drawing board a diagram of the magnet to scale, making an assumption of the space which will be required by the windings. The length of the magnetic paths in the different parts of the circuit should now be measured and the magnetomotive force required by each portion of the circuit calculated as follows. For the density at which each part of the circuit is to be operated, find from the B. & H. curve the corresponding value of H. Multiplying the value of H of that


Relation between Density and Pull per Unit Area,




Relation between Density per Unit Area and Pull

portion of the circuit in centimeters will give the Gilberts for that portion.

By adding the Gilberts required for the entire magnetic circuit, since

$$H = \frac{4\ Si}{10\ L} \qquad (14)$$

we have,

$$= \frac{H\ L \times 10}{4} = \frac{H\ L}{1.257} \qquad (15)$$

To this the total Gilberts for the circuit, divided by 1.257 will give the required ampere turns.

The radiating area of the coils should now be carefully ascertained, and by modification of equation 13, page 70, we have,

$$T^{o}\ \text{Cent.} = 83\ \frac{E\ I}{S} \qquad (16)$$

Therefore,

$$I = \frac{S \times T}{83\ E} \qquad (17)$$

Where,
T is the allowable temperature rise in degrees Centigrade
S is the radiating area in square inches,
E is the impressed electromotive force upon the coils,
I is the current which will just bring the coils up to the temperature T.

From this equation, the maximum allowable value of current may be found.

By dividing the ampere turns required by the allowable current,

$$\frac{Si}{I} = S \qquad (18)$$

the number of turns will follow.

From equation 14, we have,

$$(m) = \frac{K \times L \times I}{E} \qquad (19)$$

Where,
L is the total length of the conductor,
I is the current, and
E is the impressed electromotive force.

If we let L' represent the mean length of one turn of wire on the coils in inches, the total length will be L' x S, where S equals the number of turns.

Equation 14, page 74 may now be written:

$$(m) = \frac{K \times L' \times S \times I}{12 \times E} \qquad (20)$$

By use of this equation, the size of wire may now be found which when wound to the mean diameter selected, with a voltage E impressed, will just give the required number of ampere turns.

On page 46 will be found tables giving the diameters of insulated wires, and by use of equation 10, page 65, the number of wires which will wind in a given area may be found.

After having made allowance for insulation at the ends and bottom of the coil, this area should be made to check fairly closely with the assumed area. If it does not, it is clear that too much or not enough winding space has been assumed, and then the assumption should be made and the calculation repeated.

In addition to the electromagnets of the type shown in Fig. 33, there is a second type which is in great favor for heavy work.

The magnet shown in Fig. 34 is one of this type, which is known as the iron-clad magnet, owing to the fact that the magnetizing coils are entirely protected by an external iron jacket. The jacket serves also to complete the magnetic circuit and

forms one of the poles of the magnet.

The magnetic circuit of an iron-clad electromagnet is usually made of cast steel. The internal pole (H), the yoke (I) and the external pole (J) are all cast in one piece. The armature (K) may also be made of cast steel and is practically a round disc. The spool on whidh the magnetizing coil (s) is wound ismade with the cylindrical hole in its center to lift over the pole (H) and the flanges of the spool extend out to the inside surface of the pole (J). The spool is sometimes held in position by a flat brass ring which also fits over and is usually screwed to the pole (H). The brass ring can also be made so as to support and add strength to the protecting jacket (J).

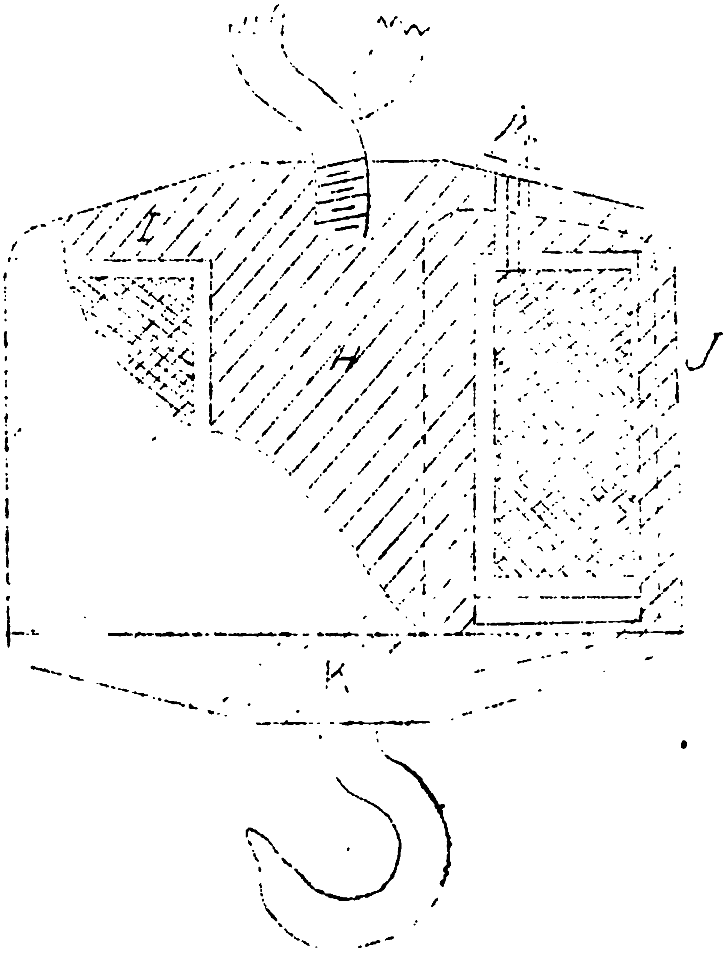


Fig. 34.

magnetic density uniform at all points of the magnetic circuit. This, however, is not essential to the efficiency of the magnet. The designer may use good judgement in making the density in the core such that the length of the coils of wire about it will not be too great, and the thickness of the outer pole such that it will not be too thin to be cast readily or to withstand the blows which may come upon it from the outside. When different areas for H and J are used or for that matter different densities, account of this must be taken in the calculations.

The principles involved in calculating the dimensions of a magnet of this type are exactly the same as those employed in designing a magnet of the "horse-shoe type" as shown in Fig. 33. In measuring the length of the magnetic circuit it is to be remembered that the mean path lies in the center of the pole (J) and of the yoke and armature (I) and (K); in the pole (H) however, it lies at a distance equal to *one third of the radius* of the surface of (H), as indicated by the dotted lines in Fig. 34. Magnetic densities ranging between 10,000 and 16,000 gausses should be used.

In determining the temperature of the winding in an iron-clad magnet, a modification of the direct method of equation 13 must be made owing to the fact that the heat generated in the winding must be liberated by conduction through the iron jacket and by radiation from the external surfaces of the yoke, outer pole and armature.

Let S' = The total external area of the yoke, outer pole and the armature expressed in square inches.

S = The sum of the outer cylindrical area, and the top and bottom discoidal areas, of the magnetizing coil.

$$T'' = \frac{1.72 \times E \times I \times D}{\frac{S + S'}{2}} \qquad (24)$$

$$= \frac{3.44\,(EI) \times D}{S + S'} \qquad (25)$$

The temperature of the coil is then, $T = T' + T''$

From the above equation it will be seen that if the outer surface be large and the sheet thin, the temperature of the coil may be made lower than it would be when radiating the same wattage in air.

Thin iron ribs are often cast on the outer surface of magnet shells to increase the radiating area.

So far we have considered the design of electromagnets to be used in sustaining a given weight, saying nothing of the distance between the pole face and the armature, in as much as these are supposed to be in contact. There are numerous cases in practice where it is desirable to produce a magnet which will lift a given weight through a considerable distance. Since the air-gap in such a magnet is of considerable length and a variable quantity during the time the magnet is operative, a special treatment is necessary in the design of such a unit. For a complete discussion of the theory tof tractional electromagnets and examples of the design of the same, the student is referred to articles in the Electrical World and the Electrical World & Engineer as follows:

Vol. 23, pp. 113, 212, and 242.

Vol. 29, pp. 196-197.

Vol. 36, pp. 125-132. 422-423.

MAGNETIC LEAKAGE.

Wherever a magnetomotive force is maintained, a magnetic field results, and a flow of magnetic lines of force is established which permeates the surrounding space. If pieces of iron lie in the path along which the M.M.F. is acting, the lines of force will mass together in passing these points, since the iron offers less reluctance than the surrounding air. Likewise if a flux be set up in a magnetic circuit composed of iron, but along which the magnetizing coils are not evenly distributed, or if a portion of the circuit is of higher reluctance than an adjoining portion, the lines of force will some of them leave the iron and pass into the surrounding air. The air forming a shunt to the magnetic circuit proper, just as a part of the return current in a trolley system leaves the track and flows through the earth. A magnetic circuit in air, i.e., an iron circuit carrying a magnetic flux and surrounded by air is analogous to a conductor carrying an electric current and immersed in a poorly conducting liquid. The fall of potential along the conductor is sure to cause some of the current to enter the liquid and more so at a point where the resistance of the conductor is greater. In a magnetic circuit the greatest leakage occurs around the path of greatest reluctance, that is around the air gaps. Since the working portion of an electromagnet or a dynamo is the air gap, the useful flux being that appearing at the air gap, the flux which leaks around the useful point is lost so far as its ability to do work is concerned and is therefore termed leakage. Whenever leakage occurs, the useful flux is always less than the total flux generated by the magnetizing coils, and the leakage coefficient is the

quotient obtained by dividing the total flux where it is a maximum by the flux passing across the useful air gap.

Since leakage always occurs, it is necessary to design the magnetic circuit and the magnetizing coils so that the leakage will be a minimum and the total flux at the point where it is a maximum, that is, at the center of the magnet coils, sufficient to give the required useful flux at the working air gap. The leakage coefficient for horse shoe magnets varies from 1.1 to 1.4, and that of iron clad magnets from 1.075 to 1.25, depending upon the density at which the iron is worked and the reluctance of the circuit. After having determined the total useful flux necessary, this must be multiplied by the leakage coefficient assumed in order to get the total flux at the point where it is a maximum in the circuit under consideration, i.e., within the magnetizing coils.

ELECTROMAGNETIC CLUTCHES AND BRAKES.

The general methods to be employed in the design of magnetic clutches and brakes is practically the same as that used in designing electromagnets to sustain a given dead weight.

In magnetic clutches there is no lateral movement of the contact surfaces when once in operation, so that we must depend for the maintainence of the transmitting torque entirely upon the magnetic tension between the two surfaces. In putting the clutch into operation however, there is lateral motion of one part with respect to the other, and this is consequently a cutting of the lines of force set up in one part by the mass of metal. The eddy currentss have the effect of magnifying from 10 to 30 times the torque due to the magnetic adhesion alone, and this effect is a factor of prime importance.

In the case of magnetic brakes, in which there is a continuous lateral movement of the two parts with respect to each other, the effect of these eddy currents is of paramount importance and the calculations should be made with reference to them, rather than the magnetic adhesion, in determining the effective torque.

In Plate 12 are exhibited some typical forms of magnetic clutches. The bearing surfaces, which are also the bounding areas of the working air gaps of the magnetic circuit, should be conical whenever it is possible to make them so, to allow for taking up the wear. Of the devices shown, Fig. 34 is a simple form of magnetic shaft coupling. When the exciting coil is energized by sending a current through it by way of the collector rings, the armature is drawn and held firmly until the current is broken. The spring washer between the two parts of the clutch, forces the halves of the clutch apart when not in operation.

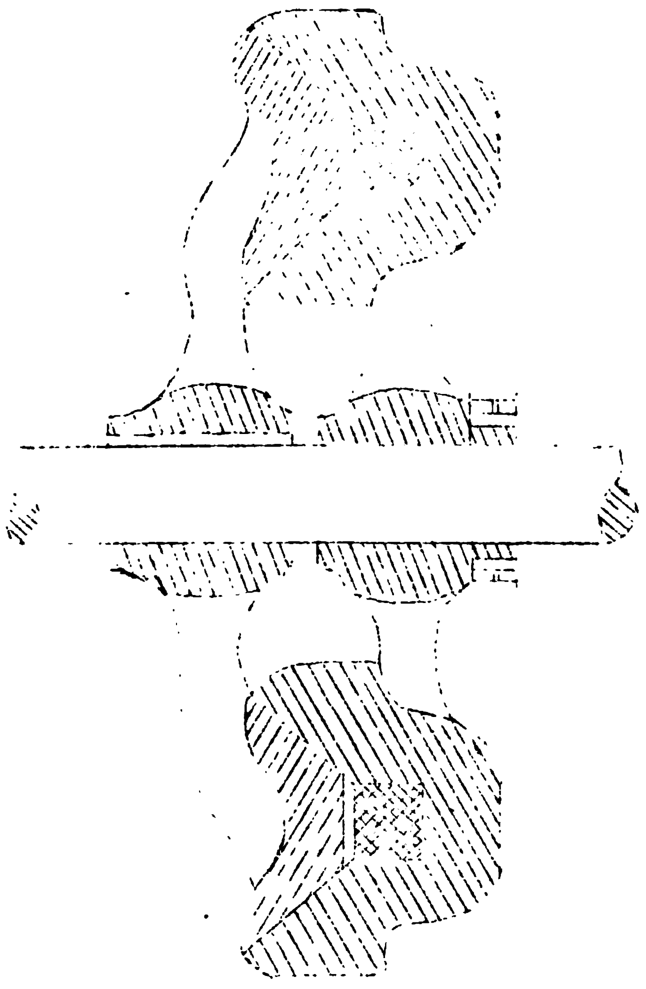


Fig. 34.

Fig. 35 illustrates a safety coupling arranged so that a particular section of the shaft may be stopped almost instantly in case of an accident. The disc (A) is fastened to the driving shaft (B), and is provided with a recess (C) in its side to receive the magnetizing coil.

The terminals of the coil are suitably connected to the collector rings mounted on the shaft and upon these bear brushes which are in turn connected to the contacts at (D). The armature disc (E) is rigidly keyed to the driven shaft (F). (G) represents a disc exactly similar to (A), but which is rigidly secured to the bearing (H), so as not to rotate. The ends of the coil (I), of this disc, are connected to the remaining two contacts at (D). The double contact switch at (D) is connected to the source of power. The operation of the device is as follows:

When the driving shaft (B) is rotated, the disc (C) will rotate with it. Now if the switch at (D) is thrown to the left the current flowing will magnetize the disc (C), and attract the disc (E) on the driven shaft (F), causing it to rotate in unison with (C). If it is desired to apply the brake, the switch at (D) is thrown to the right. The coil (I) will now be energized and the armature disc (E) will be drawn away from (A) and up against the fixed disc (G), bringing the shaft (F) speedily to rest.

In making calculations for the design of a magnetic clutch a factor of safety of 2.5 or 3 should be used, which means that the maximum torque which the clutch will transmit will be 2.5 or 3 times the normal torque which it is expected to transmit. The following expression will be useful in

calculating the sizes of the parts of magnetic clutches and brakes.

Let H.P. = The horse power to be transmitted.
F = The factor of safety assumed.
R = The mean distance of the contact areas from center of shaft, in feet.
P = The pull in pounds per sq.in. of contact area.
A = The area in square inches of the contact areas, or the area of the working air gap of the magnetic circuit in square inches.

B = The magnetic density at the air gap expressed in gausses.
C = The coefficient of friction corresponding to the materials used and to a pressure equal to P.

Then,

$$\text{H.P.} = \frac{P \times A \times 2 \times \pi \times R \times N \times C}{33000} \qquad (26)$$

$$= \frac{P \times A \times R \times N \times C}{5252} \qquad (27)$$

where,

$$P = \frac{B \times 6.45}{11183460}$$

or is taken from the curves of tractive effort as given on pages 72 and 73.

In case the surfaces of the contact area make an angle ϕ with the direction of the tension of the lines of force, ϕ being then equal to 1/2 the angle between the contact areas, a correction must be introduced by multiplying the numerator of the equation by the sine of ϕ.

In Table XIII are given the coefficients of friction of dry surfaces under gradually varying pressures, these values being taken from experimental results obtained by G. Rennie, C.E

When the contact areas are lubricated with oil, tallow or

lard, the values of the coefficients of friction should be reduced from 30 to 50 %

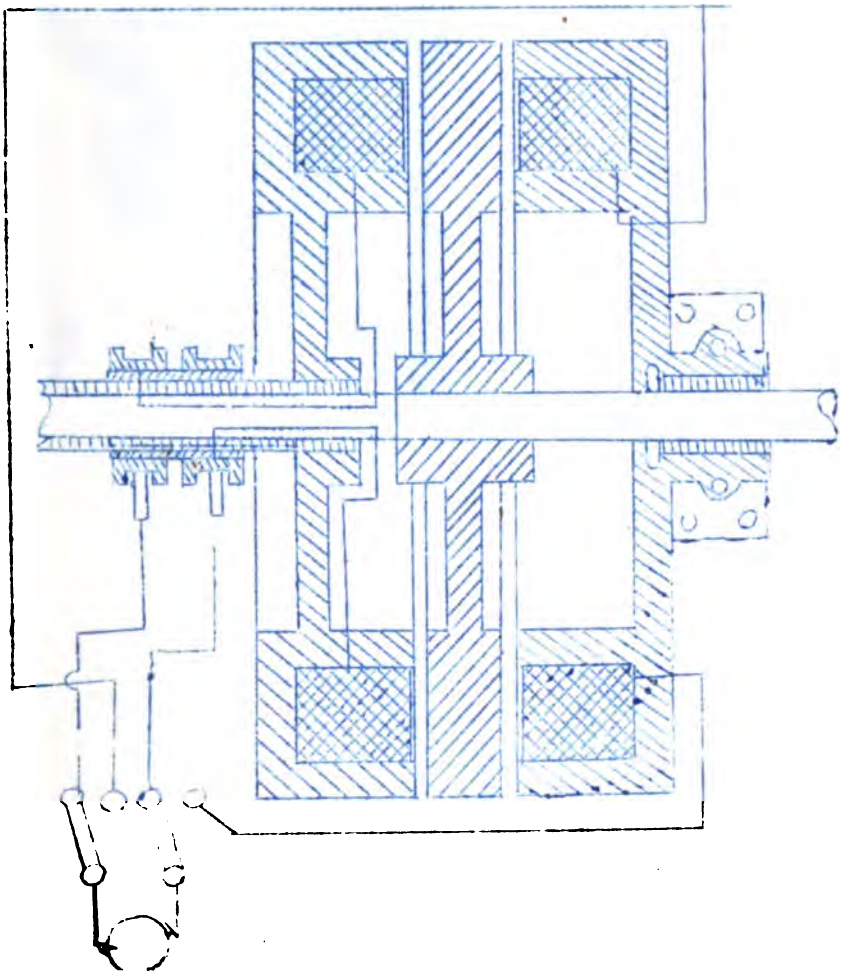
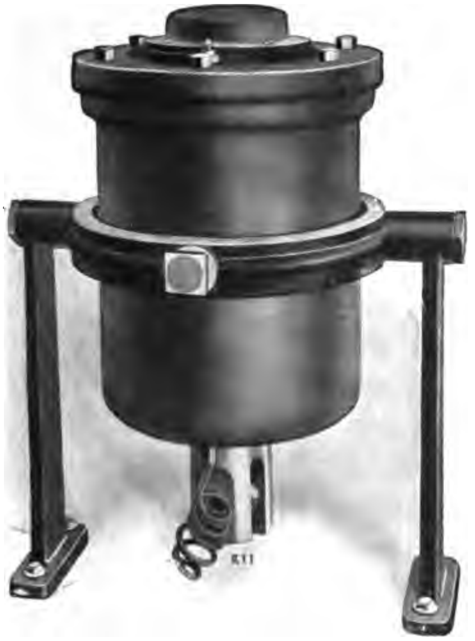


Fig. 35.

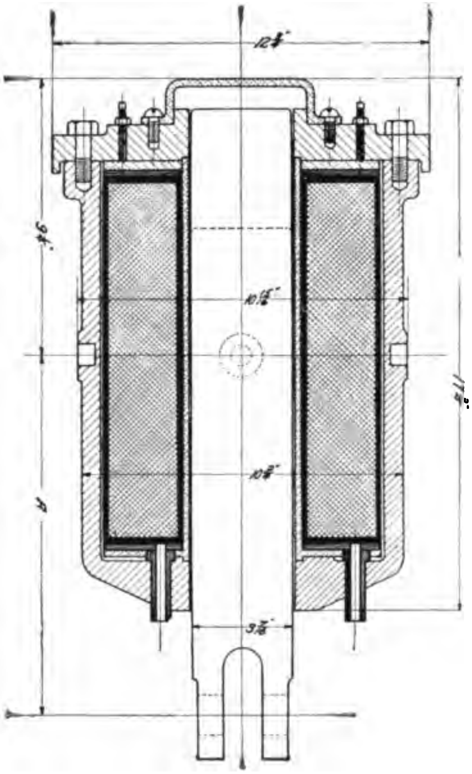
TABLE XIII.

COEFFICIENTS OF FRICTION OF DRY SURFACES.

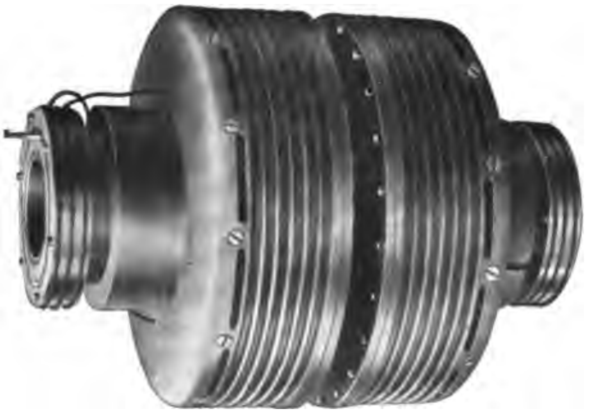
Pressures in lbs.per sq.in.	Wrt. on Wrt. iron.	Wrt. on cast iron	Cast iron on steel.	Brass on cast iron.
25	.135	.167	.155	.155
50	.151	.182	.188	.163
75	.170	.205	.215	.175
100	.187	.222	.237	.182
125	.202	.239	.257	.191
150	.217	.254	.275	.200
175	.232	.267	.280	.205
200	.250	.280	.304	.210



ELECTRO-MAGNET.



SECTION OF ELECTRO-MAGNET.



MAGNETIC CLUTCH.

ELECTRO-MAGNETIC APPARATUS.

ELECTRIC CONTROLLER AND SUPPLY CO.

Now, from equation (27, we have,

$$A \qquad \frac{H.P. \times 5262}{P \times R \times N \times C} \qquad (28)$$

and,-

$$R \qquad \frac{H.P. \times 5252}{P \times A \times N \times C} \qquad (29)$$

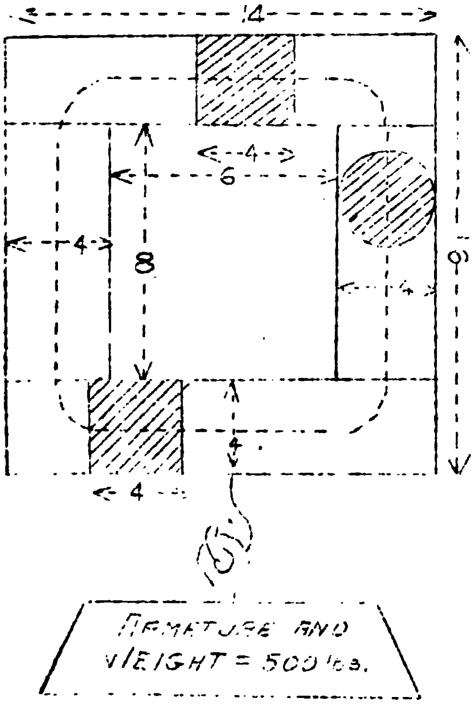
which equations will be useful in determining the approximate sizes of the clutches after the assumptions concerning the magnetic circuit have been made.

Before leaving the subject of the design of electromagnets a number of problems in the design of magnetic circuits and their solutions, as well as examples of the use of the foregoing formula will be given.

In the case of the designs given in the notes, it should be borne in mind that what is given is the final calculations, and not the different sets of calculations which are usually necessary before arriving at the result desired.

Problem 1.

There are three hundred turns on each limb of a magnet with the dimens in cm. as shown in Fig. 12. Cross section of yoke and armature 4 x 4 cm. Cores circular, 4 cm. diameter. Wrought iron used with all joints scraped. What current is necessary to sustain a weight of 500 pounds. Use curve for wrought iron and neglect leakage and reluctance of the joints.



Problem 2.

There are 400 turns on each limb of a magnet with dimensions in cm. as shown in Fig. 37. Cross section of armature 4 x 4 cm. Cores and yoke circular, diameter 5 cm. What current will be necessary to sustain 300 kilogrammes? Use wrought iron curve and neglect leakage and joints.

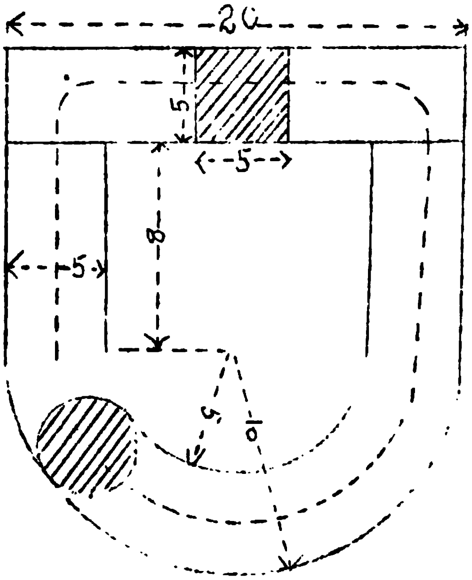


Fig. 37.

Problem 3.

If the armature in problem (1) is removed to a distance of .5 cm., what weight will be sustained by a current of 5 amp?

Problem 4.

What current will be required in the case of problem 2 to support 50 kilogrammes when the armature is removed a distance of .5 cm. from the poles of the magnet.

Problem 5.

The frame shown in Fig. 38 is of wrought iron, dimensions in cm. The test piece is 3 x 5 cm. Cross section of A A' is 8 x 5 cm. Air gap at C C' is .1 cm., and filled with brass bushing to prevent friction. Surface at B is scraped. Number of turns in coil is 300. Current in coil is 1.2 amperes. The test piece does not come in contact with the coils Find B and for the test piece when 112 pounds are required to pull the test piece away from the surface

Problem 6.

If the faframe is of cast iron, all other data remaining the same, what are the values of B and ?

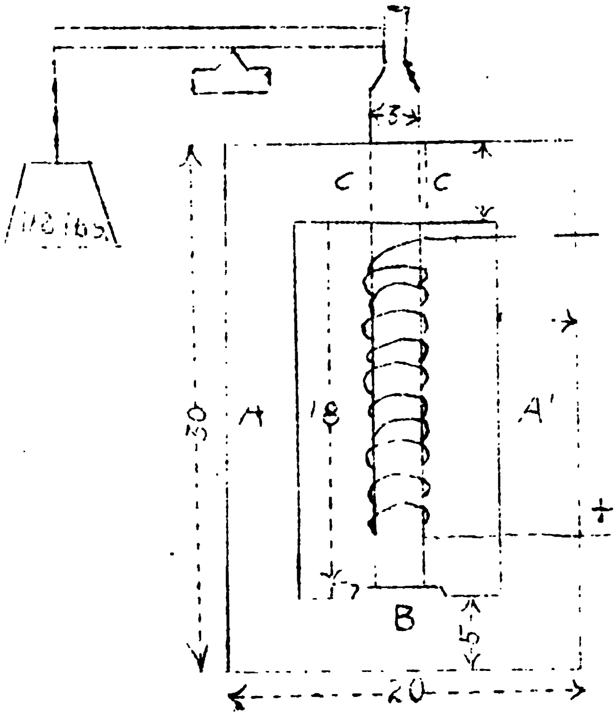


Fig. 38.

Problem 7.

If the magnetizing coil is wound equally on A and A', how many turns ampere turns will be required to produce the same result?

Problem 8.

If the armature in Prob. 2 is removed to a distance of .1 cm., what weight will be supported by a current of 6 amperes in the windings?

Problem 9.

What will be the weight supported in the case of Prob. 8 if the cross section of the magnetic circuit be doubled throughout, but the mean lengths of each portion of the circuit be kept the same and the same current passed through the windings?

Problem 10.

An electromagnet having the dimensions in cm. given in Fig. 39 will sustain 100 lbs. when .4 ampere is flowing through the two field spools in series. How many turns are there in the winding? The circuit is composed of wrought iron. The reluctance of the air gaps and magnetic leakage may be omitted from the consideration.

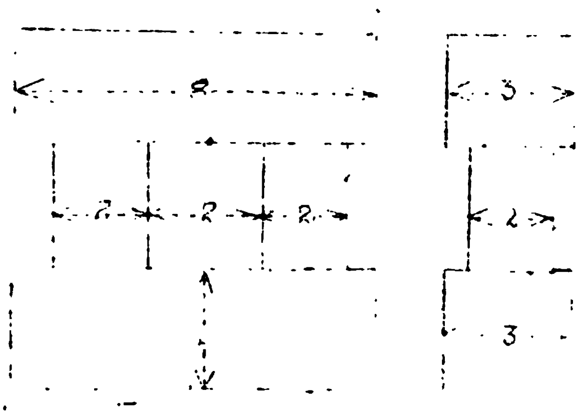


Fig. 39.

Problem 11.

If the magnet in Fig. 40 supports 87 pounds when 188 ampere turns are impressed upon its magnetic circuit, what is the length of the cores within the magnet coils. The magnet is made of wrought iron. All dimensions in cm. The yoke and armature 3 x 3 cm. cross section of the cores are circular section, 2.5 in diameter.

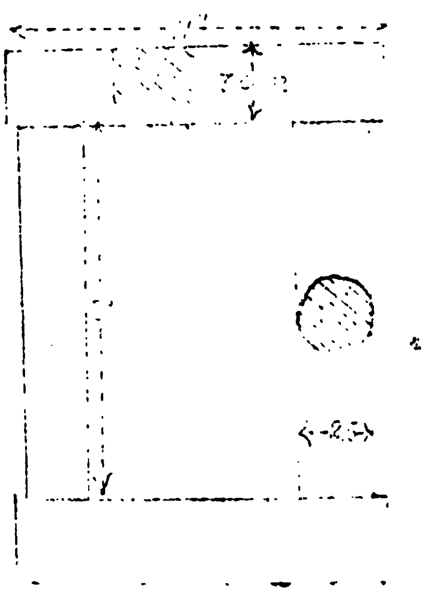


Fig. 40.

Problem 12.

The magnet shown in Fig. 41 is made of cast iron, dimensions in inches as shown. The magnet will exert a pull of 1500 lbs.

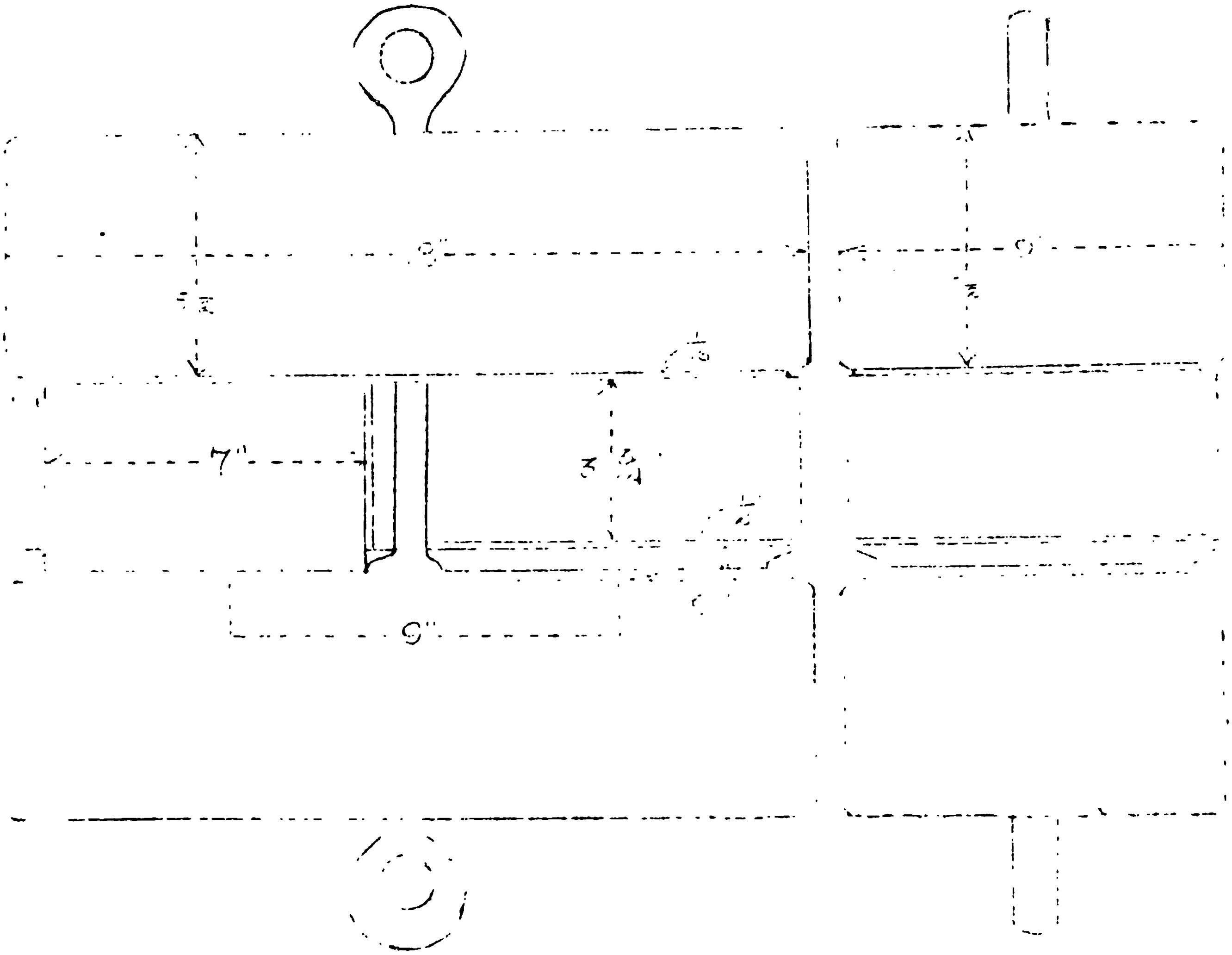


Fig. 41.

and operates on a 220 volt circuit. Allowing 800 (m) per amp what size of B. & S. wire, and how many feet of it, must be used in winding the magnet?

Problem 13.

The electromagnet shown in Fig. 42 is made of wrought iron. The dimensions as shown, in inches. Length of a single air gap is .003 inches. Determine the ampere turns necessary, when the voltage to be used is 110, current .05, Temp. 27.5 Deg. C.

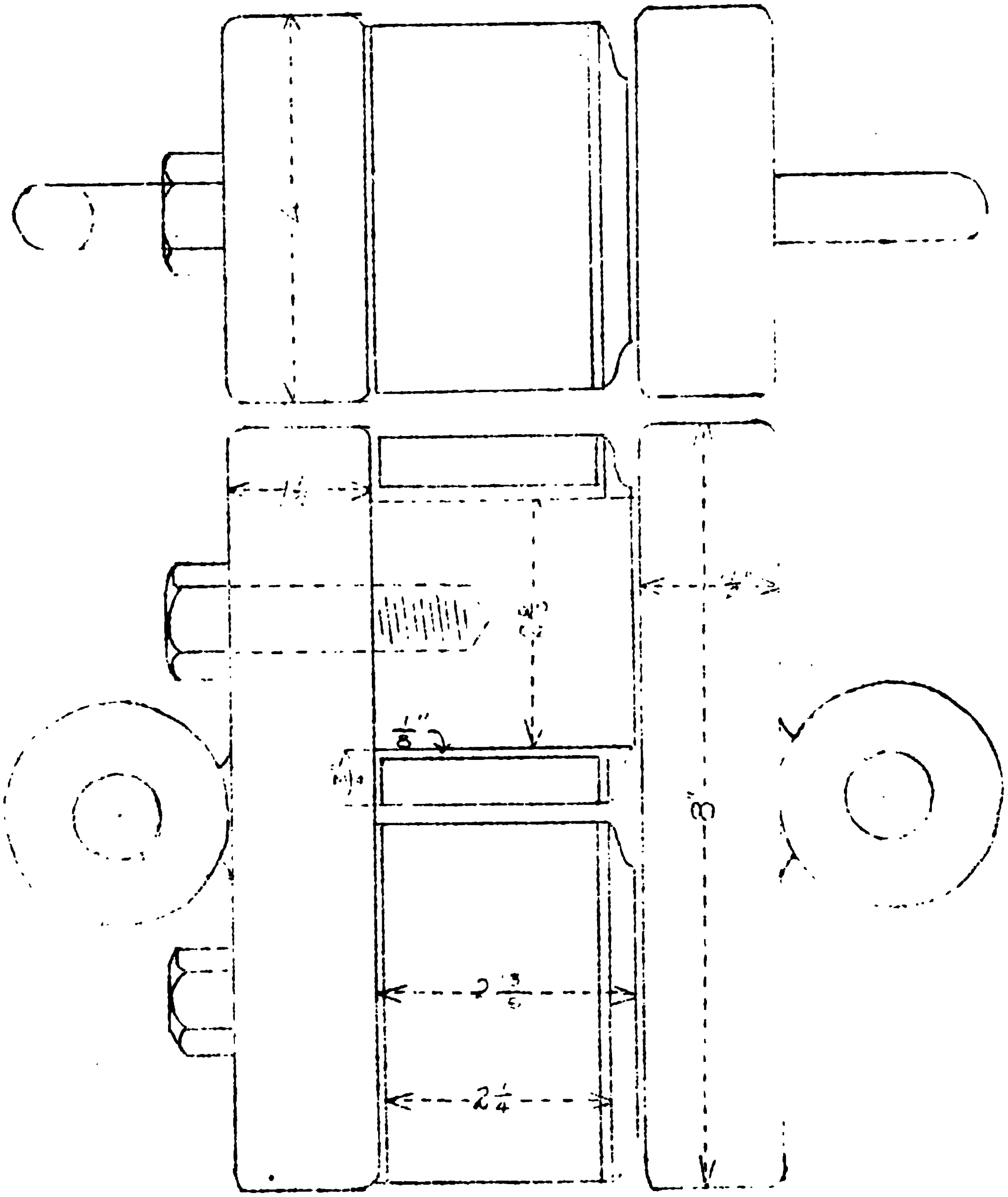


Fig. 42.

The application of the preceding methods and principles can best be illustrated by the consideration of an actual design.

We shall therefore consider the design of an electromagnet of the different types mentioned. In order to obtain a comparison, the magnetic densities and maximum pull, as well as the e.m.f. will be the same in each case.

Design No. 1.

An electromagnet of the horse-shoe type is to sustain 200 lbs. as a maximum load and is to be magnetized by a current taken from mains having a difference of potential of 55 volts.

Considering the entire magnetic circuit to be made of cast steel, from a B. & H. curve of cast steel, we find that the most economical densities to vary between 10,000 and 13,000 gausses for this material.

Assume a density of say 11,000 gausses at the polar surface, and from equation 12, page 65, we have,-

$$200 = \frac{11,000^2 \times A}{11,183,460.97}$$

whence,

A = 18.5 cm., or for a single pole face, the area is,

$$A = \frac{18.5}{2 \times 6.54}$$

1.42 square inches.

This may be checked by referring to the curve on page 73. which indicates a tractive effort of 70 lbs. per sq. in. with a density of 11,000 gausses, so that the area of a single pole face will be,

$$\frac{200}{70 \times 2} = 1.42 \text{ square inches as found above.}$$

This area corresponds to a diameter of pole face of a trifle less than 1-3/8 inches.

The leakage coefficient for a magnet of this type, where the steel is worked below saturation and the armature in contact with the pole faces, would be 1.015, a value almost negligible, so that we can make the diameter of the cores to be 1-3/8 inches and neglect further consideration of the leakage.

Assuming a length of core of 2 inches and allowing 5/8 of an inch forthe depth of winding and insulation, we find the distance between centers of cores to be as follows,-

2 x 1/2 the diam. of each core,	1-3/8 in.
2 x the thickness of the winding,	1-1/4 in.
2 x 1/8" projection of spool ends,	1/4 in.
Space between spool ends,	1/8 in.
Total,	3 inches.

The armature and yoke should project over the core somewhat so that we will make each 2 inches in width, and assuming a density of 9,000 gausses in the yoke and armature, we have the thickness,-

$$t = \frac{1.42 \times 11{,}000 \times 1.015}{9000 \times 2}$$

$$= .8808 \text{ inches, say } 7/8 \text{ inches.}$$

which should be taken for the thickness of the yoke; the thickness of the armature would be,

$$t' = \frac{1.42 \times 11{,}000}{9000 \times 2}$$ since the leakage occurs before the flux crosses the air gap,

$$= .857$$ inches, but we can make the dimension the same as the yoke, since holes must be bored in th

armature to receive the lifting hook.

We now have sufficient data to enable us to make a scale drawing, which should always be done at this juncture, in order to determine the lengths of the paths of the flux in the different portions of the magnetic circuit, and further to be able to tell whether the magnet will be properly proportioned with regard to appearance to the eye. Fig. 43 shows such a drawing, based upon the dimensions already determined.

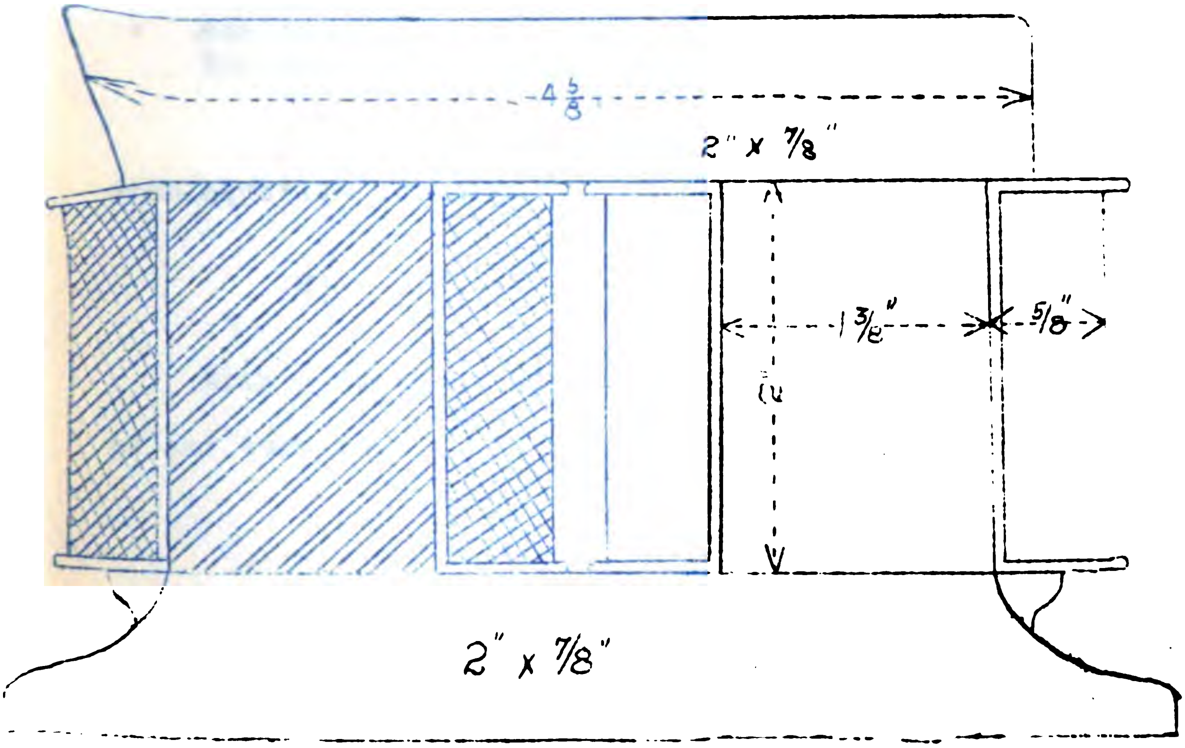


Fig. 43.

The lengths of the paths of the flux should now be measured and we can then proceed with the calculation of the magnetomotive force necessary in the windings, as follows.

For the two cores we find from the curve,

B = 11,000 gausses,
H = 17.5
L = 2 x 2 x 2.54 = 10.16 cm.
HL = 17.5 x 10.16 = 177.8 gilberts.

For the yoke and armature,

B = 9000 gausses, for which
H = 11.5,
L = 17.15 cm. (from drawing)
HL = 11.5 x 17.15 = 197.2 gilberts.

For the joints at ends of cores,

B = 11,000,
H = 11,000
L = .007 cm. (assumed as a value for the two joints)
HL = 11,000 x .007 = 77 gilberts.

Summing up, we have for the entire magnetic circuit,-

For the two cores,	177.8 gilberts.
For the yoke and armature,	197.2 "
For the joints,	77.0 "
Total for the circuit,	452.0 gilberts.

From equation 15, page 71, we have,

$$Si = \frac{452}{1.257} = 359.5 \text{ ampere turns.}$$

With a depth of winding of 5/8" as shown, the mean length of one turn is,

$$L = (1.375 + .625) \times \pi$$

6.25 inches, and from equation (20), page 75, we have,

$$(m) = \frac{12 \times 6.25 \times 359.5}{12 \times 55}$$

40.8 circular mils.

The nearest size of wire is # 34 B. & S. gauge, which has a cross section of 39.75 (m).

Assuming 800 (m) per ampere, which is a good value for coils exposed to the air, the current will be,

$$i = \frac{39.75}{800}$$

= .0496 amperes, and from this

the number of turns may be found by dividing the ampere turns by the current

$$S = \frac{359.5}{.0496}$$

$$= 7,240$$ turns on the two spools or 3620 turns per spool. From table 1, page 46, we find that No. 34 d.c.c. B. & S. wire has a diameter of .00515 inches. The number of turns per square inch will then be,

$$n = \frac{1}{(.00515)^2} = 3762.,$$ so

that the area needed for the winding on one spool will be,-

$$A = \frac{3620}{3762}$$

$$= .963$$ square inches, which checks with our assumed value of 1.875 x .5625 = 1.062, which comes from the assumed winding space, after making allowance for the insulation at the bottom and ends of the coil.

The total length of wire in the two coils will be,-

$$\frac{7,240 \times 6.25}{12} = .3775$$ feet, and from equation 11, page 51, the resistance will be,

$$R = \frac{12 \times 3775}{39.75} = 11,400 \text{ ohms},$$

which will allow to pass,

$$\frac{55}{11,400} = .0485$$ amperes, which checks with the above value of the current within .001 ampere.

The radiating area of the two coils will be, considering radiation to take place from the cylindrical surface only,-

$$S = 1.875 \times 2.625 \times 2 \times \pi = 31.4 \text{ sq.}$$

and the watts liberated will be,-

$$W = 55 \times .0496 = 2.66 \text{ watts, and}$$

from equation 13, page 70, the rise in temperature above the air will be,-

$$T = \frac{83 \times 2.66}{31.4} = 7 \text{ degrees}$$

Centigrade above air. Considering the air to be 20° C., the temperature will be 27° C.

We can now check our resistance, knowing the exact temperature at which the coil is to operate. From the curve on Fig. 29, page 56, we find that K = 10.7 for a temperature of 27° C., so that the resistance of the two coils at this temperature will be,-

$$R = \frac{3775 \times 10.7}{39.75} = 10{,}200 \text{ ohms,}$$

and the current will be,

$$\frac{55}{10{,}200} = .0340 \text{ amperes, which is but}$$

slightly in excess of the value determined above, and as the difference is an excess, rather than a value below that necessary, it is allowable.

The weight of copper in the magnet will be,-

$$\frac{3775 \times .1203}{1000} = .44 \text{ lbs.}$$

The weight of steel in the magnet will be,-

For the two cores $w = 2 \times 3 \times (1.375)^2 \times \quad \times .28 =$ 166 pounds..

For the yoke and armature,

making the weight of steel to be 6.48 pounds, and the weight of the magnet complete about 7 pounds.

Design No. 2.

An electromagnet of the iron-clad type is to sustain a maximum load of 200 lbs., when magnetized by a current taken from mains having a difference of potential of 55 volts.

For purposes of comparison we will use cast steel as in design No. 1, working at the same magnetic density, namely 11,000 gausses in the air gap.

Then from equation 12, page 65, we have,

$$200 = \frac{11000^2 \times A.}{11,183,460.97}$$

whence,

A = 18.5 cm., for the entire pole area, and the area of one pole will be,

$$\frac{18.5}{2 \times 6.45} = 1.42 \text{ sq. in.}$$

and as in design No. 1, the area of one pole being 1.42 sq. in. the diameter of the core of the iron clad magnet will be 1-3/8 inches.

Assuming a thickness of winding space of 7/8 inches, we can calculate the thickness of the outer shell, which will be,-

The inner diameter of the shell will be 1.375 + 1.75 = 3.12 in. and the area of this circle is,

$$\frac{312^2 \times \pi}{4} = 7.6 \text{ sq. in.}$$ The area of the circle whose diameter is the outside diameter of the magnet is then

$$7.6 + 1.42 = 9.02$$ square inches, and the

diameter corresponding to this area is,

$$\frac{9.02 \times 4}{} = 3.4 \text{ inches,}$$

which is about as thin as would be allowable in a magnet of this size. The yoke and armature are so proportioned that the density in these parts is uniform. From the drawing of the magnet, and a knowledge of the leakage coefficient, which is

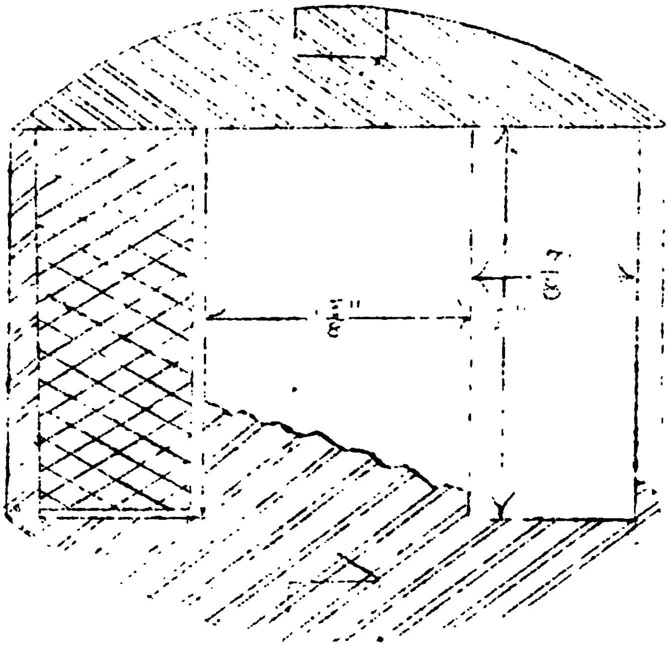


Fig. 44.

1.01 for this type, we have,

B_o = 11,000 x 1.01, or 11,120 gausses,

H_o = 18.1 for this latter density.

L_o = 5.08 cm.

H_oL_o = 13.1 x 5.08, or 91.8 gilberts for the core.

B_y = 9000 x 1.01, or 9,100 gausses,

H_y = 11.75,

L_y = 6.675 cm.

$H_y L_y$ = 78.5 gilberts for the yoke.

B_a = 9,000,

H_a = 11.5,

L_a = 6.675

$H_a L_a$ = 76.75 gilberts for the armature

B_A = 11,000,

H_A = 11,000,

L_A = .007 for the two air gaps.

$H_A L_A$ = .007 x 11,000 = 77 gilberts for the air gaps.

The total numberof gilberts will then be,
91.8 + 78.5 + 76.75 +77.0 = 324.05, and the ampere turns will be,

$$\frac{324.05}{1.257} = 257.9 \text{ ampere turns.}$$

Having determined the requisite number of ampere turns, we can now proceed to the calculation of the current, knowing the current density which should be used in an iron clad magnet, and then check up the space required for the winding with that assumed.

With a depth of winding and insulation as shown, the mean length of a turn sis 6.7 inches, and from equation 20, page 75,

$$(m) = \frac{12 \times 6.7 \times 254}{12 \times 55}$$

$$= 31.0$$

The nearest size of wire is No. 35 B. & S. which has a cross section of 31.53 (m).

Assuming 750 (m) per ampere, the current will then be,

$$\frac{31.53}{750} = .0422$$ amperes, and the number of turns must then be,-

$$\frac{257.9}{.0422} = 6625 \text{ turns.}$$

We find that 4109 turns of d.c.c. # 35 B. & S. wire will wind in one square inch, so that the cross sectional area required for our winding will be,

$$\frac{6625}{4109} = 1.614$$ square inches. We have provided a space of 2 x .875 = 1.75 sq. in. for winding and insulation, which will be sufficient, the coil being simply taped and slipped into the space after winding, without being placed on a spool.

The resistance of the winding will be,

$$\frac{112 \times 6.7 \times 6625}{12 \times 31.55} = 13130$$ ohms at a temperature of 40° C., which allows for a rise of 20 degrees above the air.

Checking the current value, we have,

$$i = \frac{55}{13130} = .042$$ amperes, which checks with the value previously determined.

The watts lost in the winding will then be,

$$W = 55 \times .042 = 2.31 \text{ watts.}$$

The total external radiating surface of the magnet is,

$$S' = \frac{3.375^2 \times \quad \times 2}{} + 3.375 \times \pi \times 2$$

$$= 17.9 + 21.0 = 38.9 \text{ square inches.}$$

The temperature of the outer surface above the air will be,

13.13 + 20 = 33.13 degrees C., which is in close accord with the value used in choosing the resistance per mil foot.

The weight of copper will be,-

$$\frac{5525 \times 3.7 \times .094}{12 \times 1000} = .326 \text{ lbs.}$$

It is apparent that the weight of both the iron and copper in this magnet is less than in the horse-shoe type, and the efficiency greater, as well as being iron clad and of more compact form, all of which favor this type for the given conditions.

Design No. 3.

It is required to design a magnetic clutch to transmit 20 horsepower at a speed of 400 r.p.m., with its magnetizing coil energized by a current taken from mains having a difference of potential of 55 volts; factor of safety 3; coefficient of friction, .17; clutch to be made of high grade gray cast iron.

From the curve of the best cast iron, we find the upper limit of density to be about 8000 gausses, and we will use this density in order to make the clutch as light as possible.

From the curve on page 73, we find the pull per sq. in. for a density of 8000 gausses to be 37 lbs. per sq. in., and assuming a mean radius of 10.5 inches = .875 feet, we have from equation 3428, page 88,

$$A = \frac{20 \times 5252 \times 3}{37 \times .875 \times 400 \times .17}$$

= 146 square inches for the area of the two poles, or 73 square inches for each pole.

Assuming a winding space of 1 square inch, the outer radius of the inner pole will be 10 inches, and the area of the entire circle of this radius will be,-

$10^2 \times \pi$ = 314.1 square inches. The area of the pole must be 73 sq. in., so that the area of the circle within the inner pole will be 314.1 - 73 = 241.1 sq. in., and the radius of this circle will be,-

$\sqrt{\dfrac{241}{\pi}}$ = 8.75 inches, the radius of the inner pole. Similarly, the outer radius of the clutch may be determined. The inner radius of the outer pole will be 10.5 + .5 = 11 inches, and the area of its circle will be $11^2 \times \pi$ = 360.1 square inches, and since the area of the outer pole must also be 75 sq. in., the outer radius of the clutch will be that of a circle whose area is 380.1 + 73 = 453.1 square inches, and the radius $\sqrt{\dfrac{454}{\pi}}$ = 12 inches.

We can now make a scale drawing of the clutch, and ascertain the mean lengths of the paths of the magnetic flux. Fig. 45 is a full size drawing of the working section of the clutch.

Assuming a leakage coefficient of 1.01, the magnetic density in the yoke andpoles will be,-

B = 8000 x 1.01 = 8080 gausses, and from the curve of gray cast iron, H for the density is 39.2; and from the drawing we find the length of the path in this portion of the circuit to be,

L 12.6 cm., so that
HL 12.6 x 39.2 492 gilberts for yoke and poles.

For the armature,

B = 8000 gausses, for which
H = 36.3, and
L = 7.2 cm. whence,
HL = 36.3 x 7.2   261 gilberts for the armature.

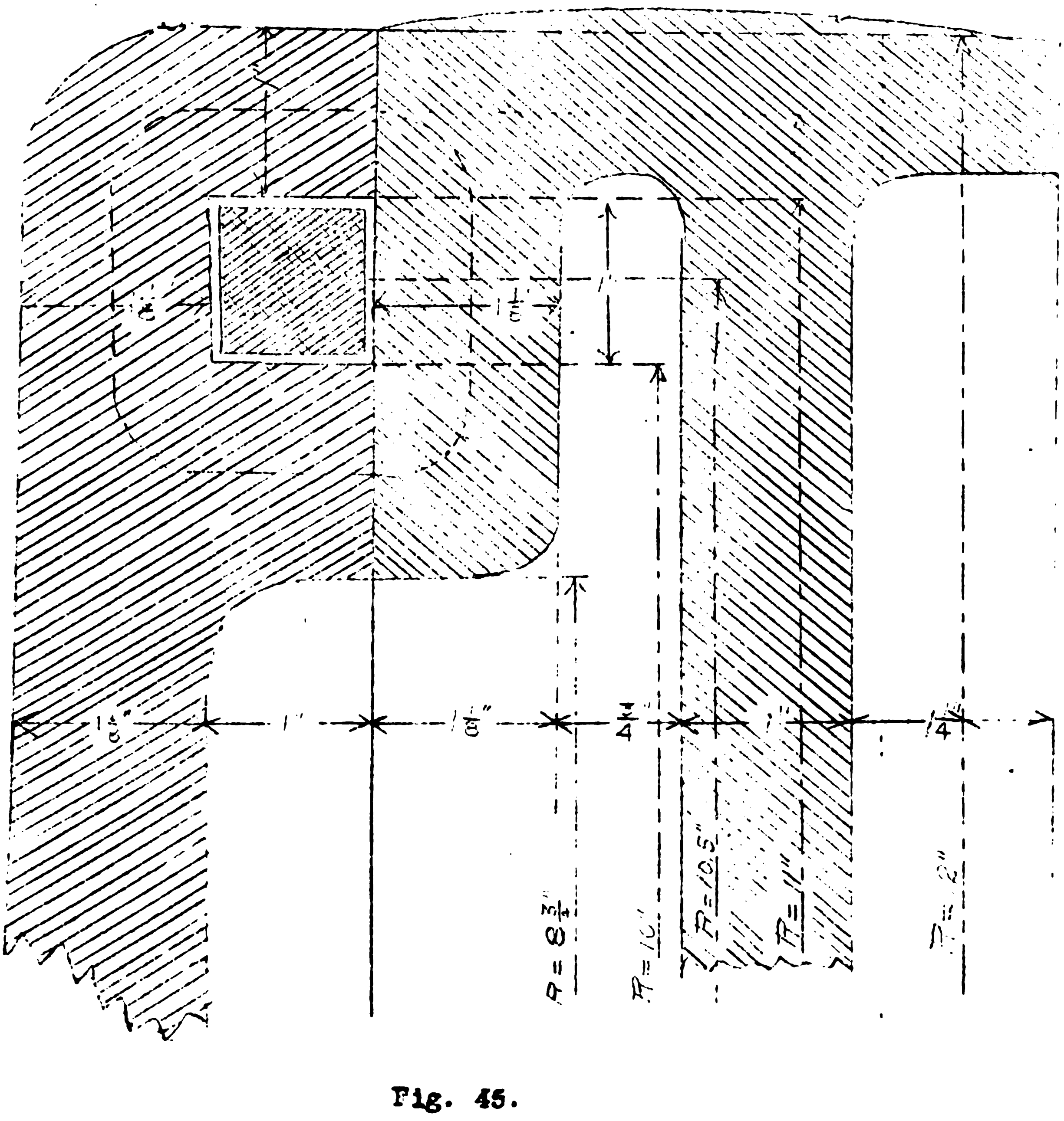


Fig. 45.

Assuming the length of a single air gap to be .001 inches, the length of a double air gap in cm. will be,

L = .001 x 2 x 2.54 = .00508 cm.

$$B = 8000,$$
$$H = 8000, \text{ so that}$$
$$HL = 8000 \times .00508 = 40.64 \text{ gilberts for the air gaps.}$$

Summing up, we have, 492 + 261 + 40.64 = 793.64, the total number of gilberts forthe magnetic circuit, and the ampere turns will be

$$\frac{793.64}{1.257} = 632 \text{ ampere turns.}$$

Assuming that the clutch will operate at a temperature of 35° C., the value of K from the curve on page 56, is 11 ohms per mil foot, and the mean length of one turn of wire is,

$$L' = 10.5 \times \pi \times 2 = 68 \text{ inches, and from equasion 20,}$$

page 75 we have for the size of wire,

$$(m) = \frac{11 \times 66 \times 632}{12 \times 55}$$

$$= 694 \ (m), \text{ and the nearest size is}$$

No. 22 B. & S. having a cross section of 645 (m).

Assuming a current density of 680 (m) per ampere, we have for the current,

$$i = \frac{643}{680} = .946 \text{ amperes, and the number of}$$

turns required will be,

$$\frac{632}{.946} = 670 \text{ turns.}$$

Referring to Table 1, we find that No. 22 wire will wind 876.3 turns per square inch, so that the space required will be,

$$\frac{670}{876.3} = .768 \text{ sq. in.}$$

Allowing 1/16 inch on each side of the coil for insulation we have a winding area of .875 x .875 = .766 sq. in., which

will accommodate the required amount of winding.

The length of wire will be,

$$L = \frac{670 \times 66}{12} = $$ 3,690 feet, and from equation 11, page

51. the resistance will be,

$$R = \frac{11 \times 3960}{643} = $$ 68.15 ohms, and checking the current we have,

$$i = \frac{55}{68.15} = $$ .804 amperes, which is .14 below the value found above, due to the fact that a sie of wire having a cross section of 694 (m) is not available. This value of the current will probably be increased somewhat, after a correction for the temperature has been made, since a rather high working temperature has been assumed.

The energy liberated in the winding will be 55 x .804 = 48 watts. The entire outer radiating surface of the clutch is

$$S = 24 \times \pi \times 3.25 + 21 \times \pi \times 7$$

$$= 244 + 462 = 706 \text{ square inches.}$$

The peripheral velocity of the radiating area of the clutch is

$$V = \frac{21 \times \pi \times 400}{12} = $$ 2200 feet per minute, and its rapid motion will increase its radiating coefficient to .0232, so that the temperature of the outside above the air will be,

$$T' = \frac{48}{.0232 \times 706} = 2.94^{\circ} \text{ C. above the air.}$$

The average thickness of the iron jacket is 1.125 inches, and the area of the coil is 4 x π x 21 = 264 square inches, then from equation 25, page 79, we have for the temperature of the

coil,

$$T = \frac{3.44 \times 48 \times 1.125}{264 + 706} + 2.94$$

$$= .19 + 2.94 = 3.13 \text{ degrees}$$

Centigrade, and the temperature will be 20 + 3.13 = 23.13° C., for which the corresponding value of K is 10.48 ohms per mil foot.

Checking hthe resistance for this new temperature, we have,

$$R = \frac{10.48 \times 3960}{643} = 64.8 \text{ ohms, and the current which}$$

will flow will be,-

$$i = \frac{55}{64.8} = .85 \text{ amperes, which is still}$$

trifle below the required value as found above, but since we have assumed a factor of safety of 3, a difference of this amount would hardly be appreciable. However, it it is desired to have the actual current .946 amperes, it may be obtained by using two sizes of wire in the coil, such that their combined resistance will be equivalent to the resistance of such a wire as would have the cross section given by equation 20, page 75, namely 694 (m).

The efficiency of the clutch working at full load will be,

$$e = \frac{20 \times 746}{(20 \times 746) + 48}$$

$$= 99.63 \text{ efficiency.}$$

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Those caring to study the subject further should consult the following articles on electromagnets and allied subjects.

Carichoff, E.R.	On the Design of Electro-magnets for Specific duty. Elec. Wld. Vols. 22 and 23.
Hering, Carl	A straight Line Proportion in the Law of the Electromagnet. Elec. Wld. Vol. 23.
Hutchinson, C.T.	On the Design of Electro-magnets for Specific Duty, Elec. Wld. Vol. 23.
Marvin, H.N.	The Electric Percussion Drill in Theory and Practice, Trans. A.I.E.E. Vol. 9.
The Holden Magnetic	Clutch, London Elec. Vol. 35.
Goldsborough, W.E.	Elec. Wld. Vols. 29 and 36.

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PART III.

THE DESIGN OF RESISTANCES, RHEOSTATS AND ELECTRIC HEATING APPARATUS.

The operation of nearly all apparatus for the production or utilization of electric currents by electromagnetic inductior and reaction between conductors and magnetic fields of force, involves at one or more points in the system, the use of rheostats or other devices by which variable resistances may be inserted in the circuit and controlled either automatically or by hand.

The design of such auxiliary apparatus is therefore important as in it in itself determines to a certain extent the efficiency and operation of the system as a whole. The more common materials used for resistance are German silver and iron wires, the latter usually given a coating by galvanizing. Some materials less commonly used are aluminum, copper, carbon, water, and the alloys of platinum and manganese which are usually used in instrument work on account of their low temperature coefficients. Primarily, the design of a resistance or rheostat depends upon the calculations based upon the dimensions and physical properties of the material selected.

Before taking up the consideration of the practical details which govern the selection of material and methods of construction, we will consider the methods of calculation simply. Where the requirements of the service do not demand extremely accurate design, the method of calculation given on page 26 may be used. Where greater accuracy is desired, as is the case of instruments and sensitive regulating devices, the following method, which

is a modification proposed by Mr. Rennerfelt, should be used. (See Elec. Wld. Volume 23, page 241.)

For any form of cross-section of conductor used for a resistance we have,

$$P = m\sqrt{x} \tag{30}$$

where, P = the perimeter of cross section of conductor

x = the area of cross section of conductor in sq. in.

m = a constant depending upon the form of cross section.

For a square $m = 4$; for a circle, $m = 2\sqrt{\pi}$, which is the smallest value we can have for m for any cross section, and for this reason, and the convenience in manufacture, circular concuctor is most always used, except for some special reason, such as securing a greater proportion of radiating area to cross section and current capacity, in which case rectangular or corrugated conductor is used.

For any form of cross section where m is known, we have,

$$S = py \tag{31}$$

$$= ym\, x \tag{32}$$

$$= fi^2 R \tag{33}$$

where,

S = the surface of the conductor in sq. in., not including the ends,

y = the length of the conductor in inches.

f = the number of sq. in. for each watt radiated.

Then,-

$$ym\sqrt{x} = fi^2R \tag{34}$$

and we may write the resistance,-

$$R = \frac{y}{x} K' \tag{35}$$

where K' in this case is the specific resistance of the material employed, and may be calculated as follows:- The Matthiessen formula for the resistance of a conductor is,-

$$K' = K'' (1 + at + bt^2) \qquad (36)$$

where,

t is the temperature in degrees Centigrade,
K'' is the specific resistance of the substance at 0° C.

The values of the constants K" and a and b are given in the following table.

TABLE XIV.

Material	K"	a	b✓
German silver,	.0000090	.00044	.000000132
Iron,	.0000040	.00480	.000001260
Aluminum,	.0000013	.00380	.000001260
Copper,	.00000066	.00380	.000001260

These constants give the resistances in ' B.A.Ohms ', and the result must be multiplied by 1.014 to reduce it to 'International Ohms'.

Combining equations 34 and 35, we have,-

$$ym\sqrt{x} = fi^2 R$$

$$= Fi^2 \frac{y}{x} K'$$

whence,-

$$mx\sqrt{x} = fi^2 K'$$

$$\sqrt{x} = \frac{fi^2 K'}{mx}$$

$$x = \sqrt[3]{\frac{f^2 K'^2}{m^2}} \qquad (37)$$

$$x = \sqrt[3]{\frac{f^2 K'^2}{m^2}} \; i \sqrt[3]{i} \qquad (38$$

which gives expressions for the area of cross section of conductor.

To determine the length of conductor, we can place in equation 34,

$$x = \frac{K'y}{R}$$

which comes from equation 35, and gives,-

$$ym \sqrt[2]{\frac{K' y}{R}} = f i^2 R \qquad (39)$$

$$y^2 m^2 \frac{K'y}{R} = f^2 i^4 R^2$$

$$y^3 = \frac{f^2 i^2 R^3}{K' m^2}$$

$$= \frac{f^2}{K' m^2} i^3 R^3 i$$

$$y = \sqrt[3]{\frac{f^2}{K' m^2}} \; i R \sqrt[3]{i} \qquad (40)$$

as the length of the conductor in terms of current, radiation, cross section and resistance. In a similar manner we may express the weight of conductor as,-

$$W = s x y$$

$$= s \left[\sqrt[3]{\frac{f^2 K'^2}{m^2}} \; i \sqrt[3]{i} \right] \left[\sqrt[3]{\frac{f^2}{K' m^2}} \; i R \sqrt[3]{i} \right]$$

$$= s \sqrt[3]{\frac{f^4 K'}{m^4}} \; i^2 R \sqrt[3]{i^2} \qquad (41)$$

which we get by substituting the values of x and y from

38 and 40 and where,

$W =$ the total weight of the conductor in lbs.

$s =$ weight per cubic inch of material of conductor.

The above forms the basis of the method of calculation, but as the formulae resulting would be cumbersome for frequent use, there is given in Table . XV a tabulation of most of the values involved and which may be substituted in the above expressions.

TABLE XV.

Temp. 60° C.,140° F.			100° C., 212° F.			150° C., 302° F.		
$\sqrt[3]{K'}$	$\frac{1}{\sqrt[3]{K'}}$	$(\sqrt[3]{K'})^2$	$\sqrt[3]{K'}$	$\frac{1}{\sqrt[3]{K'}}$	$(\sqrt[3]{K'})^2$	$\sqrt[3]{K'}$	$\frac{1}{\sqrt[3]{K'}}$	$(\sqrt[3]{K'})^2$
.0210	47.66	.000440	.0211	47.37	.000446	.0213	47.02	.000452
.0173	57.83	.000299	.0187	53.18	[illegible]	.0191	52.29	.000366
.0117	85.50	.000137	.0122	82.03	.000149	[illegible]	76.34	.000163
.00936	103.8	.0000876	.00976	102.5	.0000955	.0102	97.77	.000105

The first line gives values for German silver, for which $s = .306$; the second line is for iron, for which $s = .278$; the third line gives values for aluminum, for which $s = .093$; the fourth line in the table is for copper, for which the value of s is .320.

TABLE XVI.

Sq. In. per watt	.50	..67	.75	1.00	1.33	1.50	1.66	2.00	2.50
Watts per sq. in.	2.00	1.50	1.33	11.00	.75	.67	.60	.50	.40
$\sqrt[3]{f^2}$	.63	.763	.826	1.00	1.251	1.31	1.402	1.587	1.842
$(\sqrt[3]{f^2})^2$	.397	.582	.681	1.00	1.468	1.72	1.966	2.52	3.393

TABLE XVII.

Shape of section-	Circle	Sq.	2x1	3x1	4x1	5x1	6x1	7x1	8x1	10x1-12x1	
$\sqrt[3]{\frac{1}{m^2}}$	.430	.397	.382	.361	.342	.326	.313	.301	.291	.274	.261
$\left[\sqrt[3]{\frac{1}{m^2}}\right]^2$	.185	.158	.146	.130	.117	.106	.098	.0908	.0848	.0753	.068

In case it be desirable to arrange the circuit so as to place two or more conductors in parallel, the calculation is modified in this particular, that if there are n conductors in parallel, the value of m is n times as great as the value of m for a single one of the conductors. Hence in Table XVII we must multiply the values of $\sqrt[3]{\frac{1}{M^2}}$ by $\sqrt[3]{\frac{1}{n}}$ and the values of $\left[\sqrt[3]{\frac{1}{m^2}}\right]^2$ by $\sqrt[3]{\frac{1}{n^2}}$. If two conductors are used in place of one, and under the same conditions otherwise with respect to radiation from surface, then the total cross section will be reduced to $\sqrt[3]{\frac{1}{2}}$ 79 % and the weight to $\sqrt[3]{\frac{1}{4}}$ 63 %. With three conductors in place of one, the cross section is reduced to 60 % and the weight to 48 %.

While this may result in less cost of material, the increased cost of construction may bmore than compensate, and the two points should be considered with reference to each other

For very large resistances, the cost of materials practically prohibits the use of any other material than iron, except it be carbon, water or an alloy composed largely of iron. Resistance made of cast iron in the form of grids are largely used in thethis country where high current capacity is desired.

Carbon and most alloys have a resistance so variable with any slight variation in composition, that calculations for their use can only be made when based upon experimental data from samples of the material to be used.

For water resistance, thathe following data give results which are sufficiently correct for work where the use of a water resistance is permissable.

The values given in Table XVIII are for a cross section one foot square and one foot in length.

TABLE VXVIII.

Water, (hydrant) approximately	100.00	ohms
" with .25 % salt (by weight)	7.84	"
" " .48 % "	4.65	"
" " .70 % "	3.12	"
" " .93 % "	2,38	"
" " 1.16 % "	1.90	"
" " 1.39 % "	1.48	"
" " .174 % commercial sulphuric acid,	4.12	"
" " .437 % " " "	1.75	"
" " .724 % " " "	1.10	"
" " .985 % " " "	.85	"

Having the general method of calculation developed, it is necessary to consider the practical conditions which may modify the design. Most resistance must be constructed in sections in such a manner as to admit of their being thrown into or out of the circuit one at a time, as circumstances may require.

The number of such sections in any one resistance depends upon the purpose for which it is intended, the voltage of the

circuit in which it is to be placed, and the volume of current which is to pass through it, having direct influence upon the number and character of the contacts or terminals for the sections.

For rheostats and resistances for ordinary direct current dynamos and motor work, the number of sections may be determined from Table XIX, which represents closely average American practice and provides a sufficient number of contacts to prevent undue sparking.

TABLE XIX.

n = 2 H.P. 8 for 110 volt motors.
n = 2 H.P. 10 for 220 volt motors.
n = 2 H.P. 15 for 500 volt motors.
n = 3 H.P. 20 for dynamos of all voltages.

DATA FOR SURFACE OF CONTACTS.

If n be the number of contacts, then for convenience in connecting, there must be n - 1 sections in the resistance. The least area of surface which should be exposed to one set of brushes by each contact may be determined by use of Table XX, but in many cases there should be provided a greater area than there indicated, in order to present sufficient surface and material for mechanical strength and to stand the wear. The contacts may preferably be made of phosphor bronze.

TABLE XX.

Kind of Contact.	Amperes per sq. in.
Copper brush,	150 to 200
Carbon brush,	30 to 50
Copper on copper,	60 to 100
Brass on brass,	40 to 75
Copper screwed to copper,	100 to 200
Copper screwed to brass,	60 to 160

There are various methods of supporting the resistance in the rheostat, which in all cases must be absolutely fire proof. Perhaps the most common method is to coil the wire into spirals, which is an inexpensive method but not at all economical of space. Where this method is employed, the coils should have between them a space of 3/16 inches for 110 and 220 volt circuits and 1/4 inche for 500 volt circuits. The diameter of the coil should vary with the size of the wire used, and may be determined approximately from the equation,-

$$d = \frac{\sqrt{(m)}}{1100} \quad 10 \text{ times the diameter}$$

of the wire. (42)

where d is the diameter of the coil in inches.

From equation 42 the length of the wire is known and from the following equation (43) the length of the spiral coil may be calculated.

$$L' = \frac{y}{\pi \, d \, S'} \qquad (43)$$

Where,

l' the length of the spiral in inches.
S' the number of turns in the spiral per inch, which

depends upon the size of wire used and should be such that when the spiral is stretched in position there will be about .1 in. between each turn. When such a spiral coil is used it may be divided into sections and each end of a section secured through a porcelain bushing to an end plate, which should be carefully designed, since with large coils the combined tension exerted by them is often very great. Care should be taken to bring a uniform pressure upon the porcelain or there will likely be a fracture, resulting in a ground on the rheostat frame.

Another convenient method of mounting is to place the resistance wire in a continuous spiral, to which leads are tapped, and which is wound back and forth over large grooved porcelain insulators, strung on rods at either end of the rheostat frame.

A third method, and one often used, especially for rectangular conductor, consists in winding the resistance upon a frame such as is indicated in Fig.46. With this construction, for small wire or strip conductor, the distance pieces are usually wound with asbestos paper and are of such size that the distance between the surface of the conductors from layer to layer is from 1/8 to 1/2 inches. When these conditions are observed, the following equations will apply for the calculation of the space required for the resistance wire

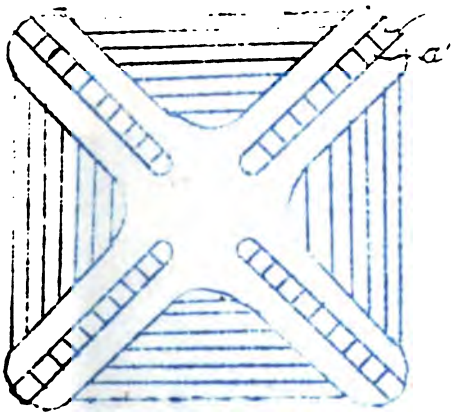
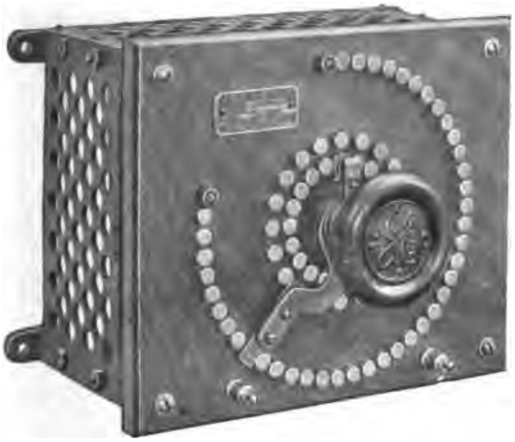
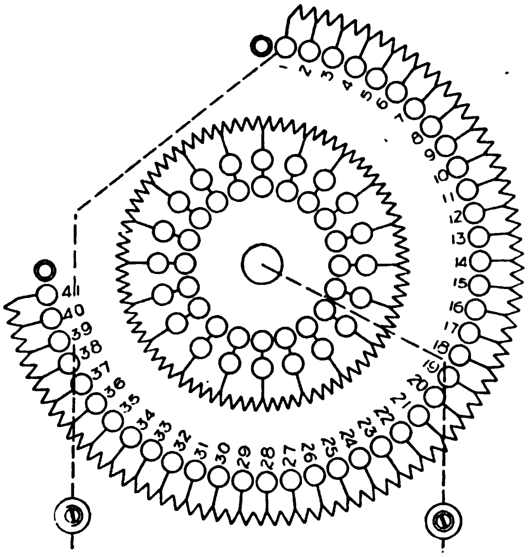
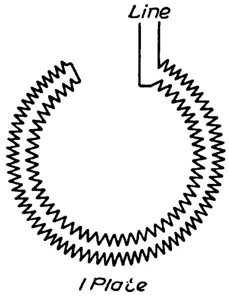


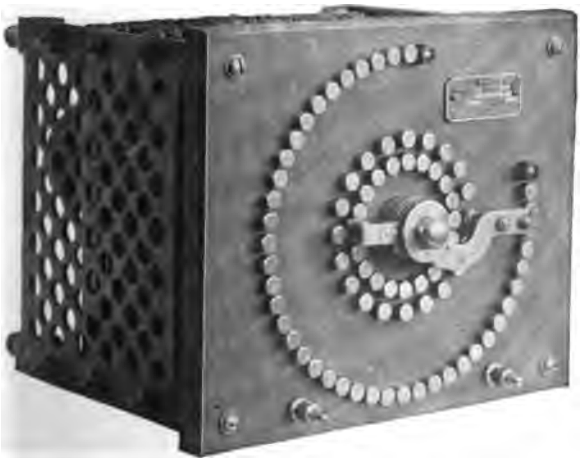
Fig. 46.

Let c = the distance between the centers of the wires in adjacent layers in inches, which is equal to the thickness of the wire plus the distance between









GENERAL ELECTRIC RHEOSTATS

n = the number of turns per raidradial layer.

L_1 = the length of a side of the inside turn inches, and may be assumed some convenient distance.

L_2 = the length of a side of the outside turn in inches.

L_3 = the length of a mean turn in inches.

b = the number of radial layers, or the number of turns in an axial layer.

S' = The total number of turns in the rheostat.

y = the length of the wire in the rheostat in inches.

Then,-

$$L_2 = \sqrt{\frac{yc}{b} + L_1^2 - 3L_1c + 2.25\ c^2} \qquad (44)$$

$$L_3 = 4L_1 - 6c + 4\ cn \qquad (45)$$

$$n = \frac{L_2 - L_1}{2c} + 1 \qquad (46)$$

The '1' being added in equation 46 to take in the first layer.

$$S' = bn = b\left[\frac{L_2 - L_1}{2c} + 1\right] \qquad (47)$$

$$y = S' \times L_3 \qquad (48)$$

Another method of mounting ribbon conductor in a rheostat is to wind it spirally with a narrow strip of asbestos paper so as to cover about one-half of its surface, and then wind the covered conductor into a flat roll and place it in a proper frame to receive and support it. In this case the radiating surface is confined to the uncovered edges of the wire and the outer surface of the outside turn, owing to the fact that the most of the flat surface is covered by the insulating strip.

A method which is largely used at the present time in the construction of street railway motor starting resistances, is to wind German silver wire upon asbestos tubes about one inch

in diameter and one foot long. After winding the tubes are mashed flat and bent into a V shaped section about 1.25 inches wide with a depression of about .25 inches, and a foot long as before. These are stacked one on the other with mica insulation between and held firmly together in packs about six inches high, in a suitable frame. Thepacks are placed so that radiation can take place from their exterior surfaces, as in the case of the flat rolls referred to above.

It is well known that an insulated wire suspended in air will carry a current of given value at a lower temperature than the same wire without the covering, other conditions remaining the same. By covering the insulation with a metal coating, or by placing a flat coil of wire between sheets of mica and clamping metal sheets over those, the radiating capacity of the wire is increased and consequently the current carrying capacity at a given temperature.

There are several special forms of rheostats which consist of a resistance buried in a non-conducting enamel or cement, in such a manner as to entirely confine the resistance wire in its position, whatever the temperature, and at the same time afford a large radiating surface.

The enamel is of special manufacture and encases the wire so as to insulate it from the cast iron radiating plate. The injurious effects of linear expansion of the resistance wire with increased temperature are avoided by the zigzag form into which the wire is bent. By this means the expansion is so distributed as to not crack the enamel.

By imbedding the wires in enamel both the cross section and the length of wire required for a rheostat of given capacity

is greatly diminshed, and the mechanical strength of the wire need not be considered, since the wire is supported on all sides.

For continuous service, from 8 to 10 watts can be radiated per square inch of resistance wire surface without difficulty, and under special conditions as high as 20 watts per square inch can be continuously radiated.

The following may be said of this form of rheostat.-

1. It is absolutely fire-proof, and is never subjected in practice to a temperature so high as that to which it is subjected in the process of manufacture.
2. It is durable, since the wires can not deteriorate from oxidation, electrolysis, etc.
3. It requires less than 5 per cent of the cubic space required by the ordinary coiled wire rheostat of the same capacity.
4. It is cheap, for a certain resistance any carrying capacity can be obtained by the use of a wire whose cross section and length will both be but one tenth of that required for a wire used in air.

An enamel is best defined as a vitreous substance fused to a metalic surface. Chemically, enamels consist of easily fused salts, such as the silicates and borates of sodium, potassium and lead, to which various metalic oxides are added when it is desired to impart color to the enamel. These varieties of glass are pulverized, made into a paste which is spread over the surface to be incrusted and exposed to a moderate temperature in a muffle heated in an enameling furnace. The vitreous substance soon becomes sufficiently fluid to spread itself over the metalic surface, to which it closely adheres. The metal

surfaces are previously cleaned with dilute sulphuric acid.

Paris' composition for enamel consists of 130 parts of broken flint glass, 20.5 parts of carbonate of sodium and 12 parts of boracic acid.

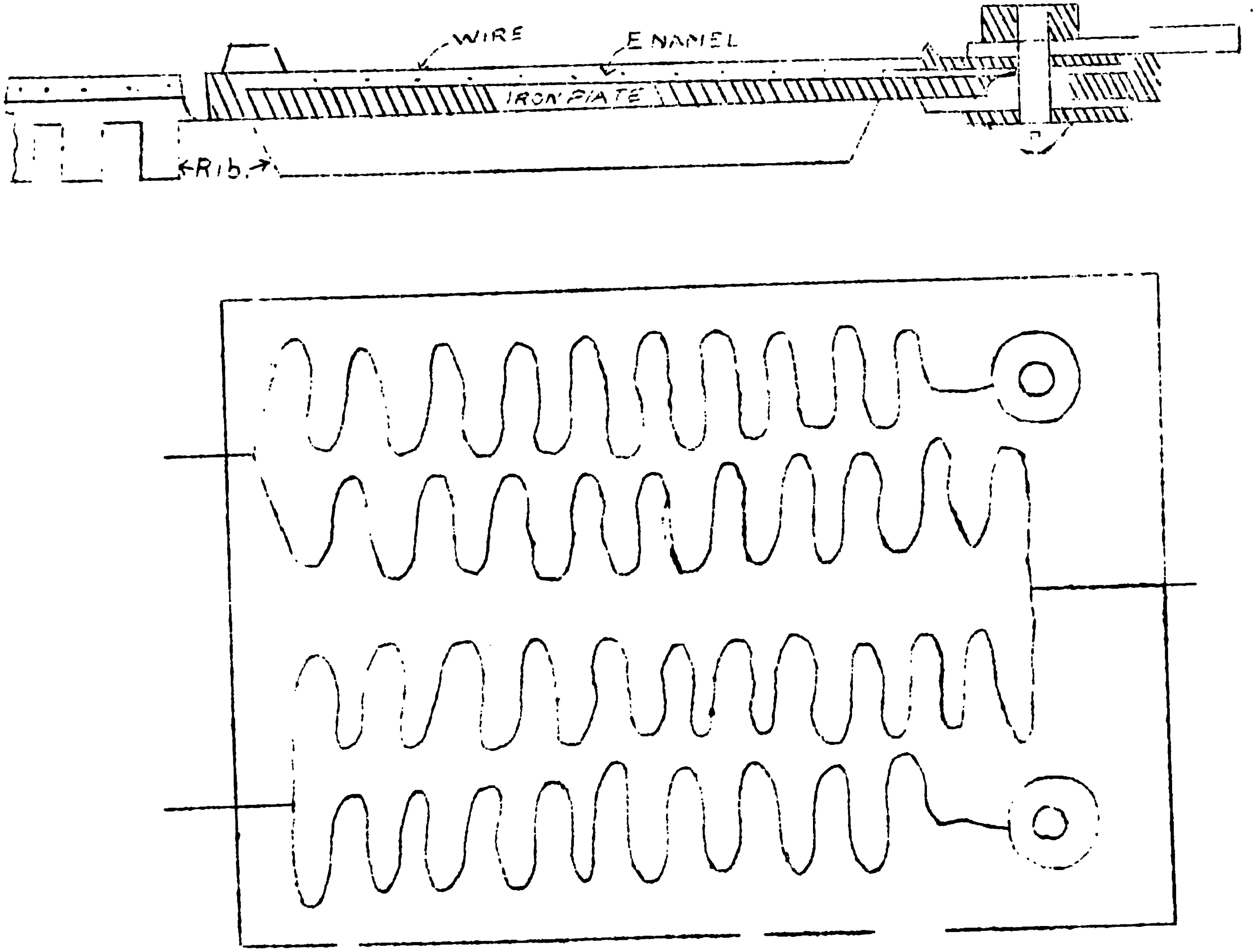


Fig. 47.

In designing an enamel rheostat, the relation between the temperature developed in the rheostat and the energy to be liberated can be determined as follows:-

Let T_c = The temperature of the wire above the temperature of the air in degrees C.

T_o = The temperature of the outside surface of the enamel above the temperature of the air in degrees C.

T_e = The temperature of the surface of contact between the enamel and the cast iron radiating plate above the air

in degrees C.

T_r = The temperature of the outside surface of the cast iron radiating plate above the air in degrees C.

A_c = The area in sq. in. of the wire.

A_o = The area in sq. in. of the outside or exposed surface of the enamel.

A_e = The area in sq. in. of the surface of contact between the enamel and the cast iron radiating plate.

A_r = The area in sq. in. of the outside or exposed surface of the cast iron radiating plate.

D_o = The average distance in inches between the surface of the wire and the outside surface of the enamel.

De = The average distance in inches between the surface of the wire and the surface of contact between the enamel and the cast iron radiating plate.

D_r = The average distance in inches between the outer and inner surfaces of the cast iron radiating plate.

W_r = The energy expressed in watts that is liberated from the outside surface of the cast iron radiating plate.

W_o The energy expressed in watts that is liberated from the outside surface of the enamel.

Then,-

$$T = \frac{83 \times W_o}{A_o} \tag{49}$$

and,-

$$T_r = \frac{83 \times W_r}{A_r} \tag{50}$$

$$T_c = T_o + \frac{94 \times W_o \times D_o}{A_o + A_c} \tag{51}$$

$$= T_r + \frac{94 \times W_r \times D_e}{A_c \quad A_e} + \frac{1.18 \times W_r \times D_r}{A_e + A_r} \tag{52}$$

The total amount of energy liberated from the resistance wire is equal to $W_o + W_r$, and the relative amount of heat liberated from the enamel and radiating plate may be determined as follows.-

Assume that 10 or 12 watts are liberated per square inch of area of the resistance wire. Make $A_r = 4 A_o$, and approximating the percentage of the energy which will be liberated from the radiating plate, usually about 80 %, decide upon the allowable value of T_r and solve for A_r and A_o, assuming that .012 watts will be radiated per square inch per degree rise in temperature. Now approximate the values of D_o, D_e, D_r and A_c. Usually $A_e = A_o$ and $D_c = 2D_e$. The values of T_c can now be solved for by both equations 51 and 52, and if the values obtained by the two equations are not the same, the values of some of the assumptions must be altered, preferably D_o and D_e should be varied until T_c is given the same by both equations. Then since,-

$$A_c = 2\pi r L \times 12, \qquad (53)$$

Where,
r = the radius in inches and ,
L = the length in feet of the wire and since,

$$R = \frac{L \times K'k\ .7854}{\pi r^2 \times 1000000} \text{ ohms} \qquad (54)$$

and,

$$L = \frac{1000000 \times \pi \times r^2 \times R}{K' \times .7854} \text{ feet} \qquad (55)$$

therefore,

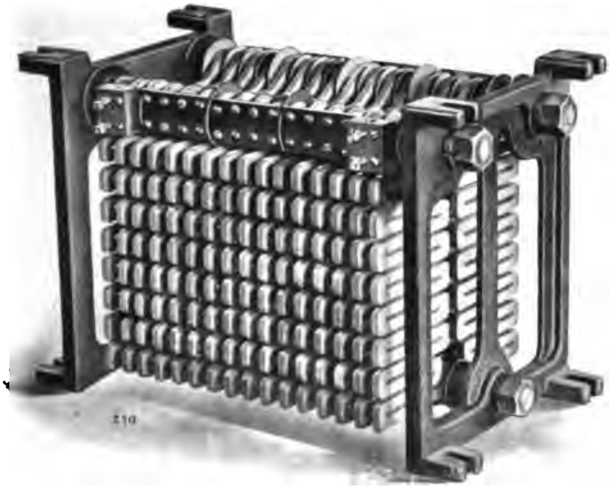
$$\frac{2000000 \times \pi^2 \times R \times r^3 \times 12}{.7854 \times K'} \qquad (56)$$

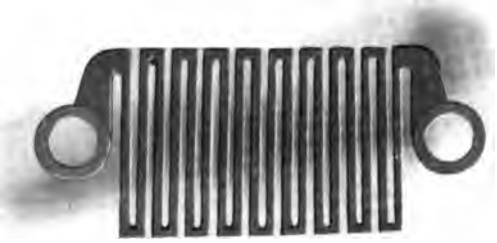
from which,

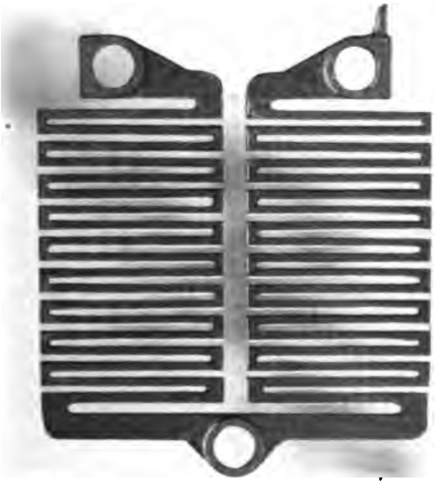
$$r = \sqrt[3]{\frac{A_c \times K' \times .7854}{2000000 \times R \times 12 \times \pi^2}} \qquad (57)$$

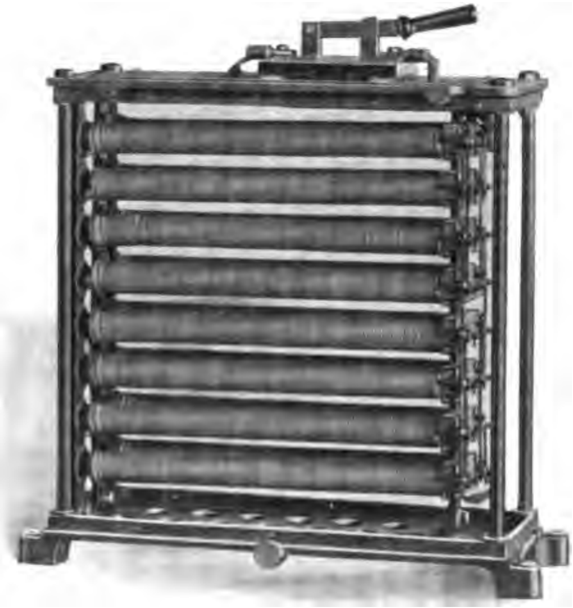
and since A_c and Rr are known, the length L of the wire is readily found.

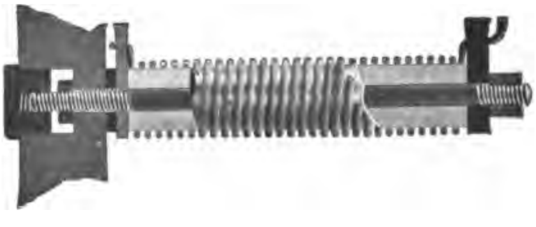
The enamel should be made as thin as is consistent with strength owing to its low radiating coefficient, and the cast











IRON RESISTANCES.

ELECTRIC CONTROLLER AND SUPPLY CO.

iron plate, by means of corrugated surfaces or ribs, should be given as large a radiating surface as the general limitations of the design will admit.

ELECTRIC HEATERS.

Electrical methods of heating can not be used with profit except power be very cheap and in special cases as in electric cars, tin shops, laundries, restaurants, etc., where the conditions are favorable to this, more than to any other method of heating. Such conditions are becoming more common, and as the system is one of greatest efficiency of distribution of heat, it is therefore one of considerable and growing importance.

In general, there are four conditions to be observed in this class of work.-

The apparatus must be thoroughly insulated and absolut fire-proof.

The temperature of the conductor must be kept well below a value at which oxidation or crystallization is likely to occur.

A radiating surface must be provided depending upon, and sufficient for the purpose of theapparatus.

The proper resistance for the voltage to be employed must be obtained.

At present, the most important application of the electric heater, aside from electric welding and forging, is in electric railway work and data will be given later on which may be based designs for this particular class of work.

Iron wire oxidizes at about 900° F. and therefore should not be heated to a temperature exceeding 400° F.

One British Thermal Unit is equal to 1047 watts, and if the heat radiated from the occupants of a car or room is to be taken into account, it should be remembered that an average person radiates heat at the rate of .053 B.T.U. per second.

An ordinary 24 ft. car under average conditions requires a radiation of .12 B.T.U. per second within the car to keep the temperature inside the car 1° F. above that of the outside air, and a proportional increase in the radiated heat as the volume of the car or the difference of temperature between the outside air and that within the car is increased. This applies when the doors are closed promptly and there is no considerable wind blowing.

According to J.F.McElroy, the radiation of 10 B.T.U. per second is sufficient to properly heat a 24 ft. car in the coldest weather and the radiation required can be increased proportionally as the volume of the car.

Iron wire is best adapted for use in the construction of heaters on account of its cheapness and high temperature coefficient, which, should free radiation be interrupted, will increase the resistance of the wire sufficiently to cut down the current and maintain the temperature of the heater within a safe value. In Fig. 48 is given a set of curves plotted from experimental data from tests of a commercial heater and exhibiting the principle just referred to.

The heater was cut into the circuit and its temperature began at once to rise, as indicated by the curve of temperature and time.

After being allowed to run 48 minutes, the openings in the base were covered with asbestos cloth and after operating

in the base were covered with asbestos cloth and after operating 43 minutes in this condition, the cloth was removed. Readings of time, temperature and current were taken and are shown in the two curves. It will be observed that the ordinates of the current curve B are approximately inversely proportional to the ordinates of the temperature curve A. This variation is due to the change of resistance with change of temperature in iron wire.

As a guide to the designer, a discussion of the methods of construction of some of the best known forms of commercial heaters is given on the following pages.

THE BURTON ELECTRIC CAR HEATER.

German silver wire is bent into a zigzag form and placed in a hollow space between two castings. The space between the castings is filled with powdered fire-clay to prevent the wire from being oxidized and from coming in contact with the iron portions. The iron castings are made with a rough exterior to increase the radiation of heat.

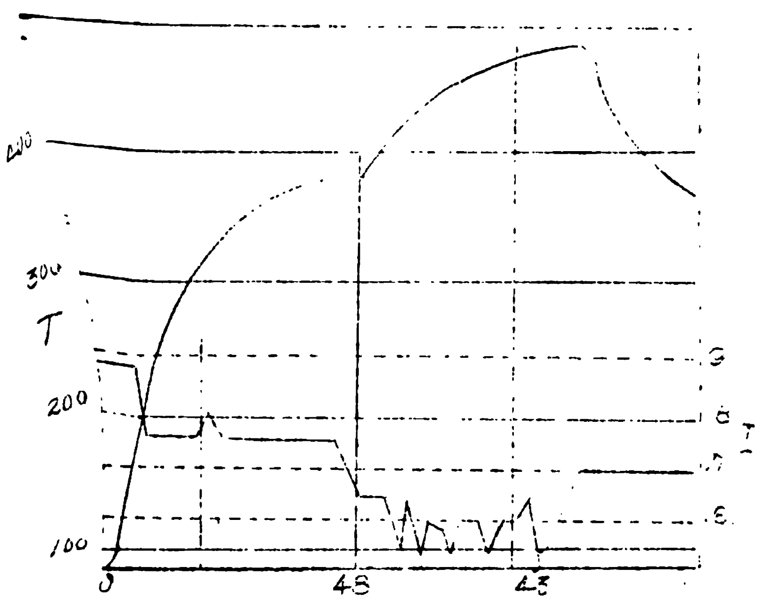


Fig. 48.

THE WHITTINGHAM ELECTRIC-CAR HEATER.

This heater is composed of wrought iron pipes running full length of the car on either side, the ends fitted to suitable castings Each pipe contains a coil of iron resistance wire, enclosed in a heat conducting, insulating tube,

and both the pipe and the tube are packed with pure silica. The current capacity is 3 amperes on 250 volts, or 750 watts. 5000 watts can be liberated by the heater without injury. In use on a 500 volt circuit, two heaters are connected in series.

CONSOLIDATED CAR HEATING CO'S HEATER.

In the construction of this heater, cylindrical porcelain tubes provided with a spiral groove on their surface, are slipped on a 5/8 inch square iron rod, and a porcelain disc is placed at each end of the heater. A #20 B.& S. galvanized iron wire is wound in the spiral groove.

THE WHITTINGHAM ELECTRIC CAR HEATER. #2.

The Whittingham Co's second heater consists of twelve wrought iron tubes one inch in diameter and six feet long, having a total radiating surface of 2592 square inches. Each tube contains three strands of #20 B.& S. German silver wire, twisted together and inserted in a 1/4 inch glass tube, the whole being filled with clean sand. This heater has a low temperature coefficient and permits a constant current to flow under a wide difference of temperature, and does not show the self-regulating qualities so noticeable in iron wire heaters.

In connection with this discussion of electric heaters, it is interesting to note that a bank of incandescent lamps, taking the same power, give the same heating effect as an ordinary wire heater. They are identical with the heater in every respect, so far as experimental results show, except that they give light also, and perhaps a better diffusion of heat.

The foregoing principles laid down for the design of heaters and resistances will be applied in a number of designs found on the following pages.

Design No. 4.

It is required to design a rheostat to be used in starting a 3 H.P., 500 volt motor, the efficiency of the motor at full load being 82 %.

The normal current of the motor is,-

$$\frac{3 \times 746}{500 \times .82} = 5.46 \text{ amperes,}$$

so that if double the normal current be allowed to flow at starting, the maximum starting current will be 10.92 amperes. The total resistance of the rheostat must then be,-

$$R = \frac{500}{10.92} = 45.8 \text{ ohms.}$$

From Table XIX, page 118, we find that the required number of contacts is,-

$$n = 2\sqrt{3} + 15 = 16.17,$$

say 18 contacts, and the required area of each contact from Table XX, page 119, using copper on copper, will be,-

$$\frac{10.92}{70} = .156 \text{ sq. in.}$$

It is readily seen that this is not sufficient for mechanical strength or durability, so we will provide a contact 1-1/4" x 3/8" x 1/8".

If German silver wire be used as the resistance, and assuming a moderate radiation of say 1 watt per square inch at 100° C., the dimensions will be as follows,-
From equation 38, page 114, the cross section is,-

$$x = 1.00 \times .000446 \times .43 \times 10.92 \times 2.22$$

$$= .004208 \text{ sq. inches,}$$

B. & S. wire having a cross section of 6530 (m).

From equation 40, page 114, the length of conductor will be,-

$$y = 1.0 \times 47.37 \times .43 \times 10.92 \times 45.8 \times 2.22$$

$$= 22{,}615.8 \text{ inches},$$

$= 1884$ ft, 7.8 inches, and from equation 41, page 114, the weight of conductor will be,-

$$W = .306 \times .004208 \times 22{,}615.8$$

$= 29.12$ lbs., which at 40 ¢ per pound, gives a cos of material of $11.65, which is prohibitive for ordinary commercial work, making the rheostat too expensive, so the resistance must be made of iron.

Case 2.

With iron wire we have from equation 38, page 114, the length to be,

$$x = 1.00 \times .000329 \times .43 \times 10.92 \times 2.22$$

$$= .003105 \text{ square inches},$$

= a # 14 W & M wire which has 6400 (m).

From equation 40, page 114, the length of conductor will be,-

$$y = 1.0 \times 55.12 \times .43 \times 10.92 \times 45.8 \times 2.22$$

$$= 26{,}315.8 \text{ inches},$$

$$= 2192 \text{ ft. } 11.8 \text{ inches}.$$

The weight will then be, from equation 41, page 114.

$$W = .278 \times .003195 \times 26315.8$$

$= 34.41$ lbs., which at 5 ¢ per pound costs $1.72, showing a saving of $9.93, as compared with German silver. The weight of conductor is still considerable and may be reduced by using special rectangular conductor which will probably not increase the total cost, although the cost per pound will be slightly increased.

[illegible]

[illegible] is [illegible] to [illegible]

[illegible] where [illegible] the [illegible]

Case 3.

With rectangular conductor of iron with proportions of sides of 12 to 1, we have from equation 38, page 114.

$$x = 1.0 \times .000529 \times .261 \times 10.92 \times 2.22$$

$= .002855$ square inches, which will require a cross section of dimensions .1845 x 0154 inches.

From equation 40, page 114, the length of conductor required will be,

$$y = 1.0 \times 55.12 \times .261 \times 10.92 \times 45.8 \times 2.22$$

$= 15{,}973.1$ inches,

$= 1331$ feet .

From equation 41, page 114, the weight will be,

$$W = .278 \times .002855 \times 15973.1$$

$= 12.67$ lbs., which at a cost of 8 ¢ per pound will cost $1.01 and reduces both the cost and weight to as low a limit as seems possible without the introduction of complications which would over-balance the reduced weight.

The winding may be supported in a frame as indicated in Fig. 46, and assuming a length of inside turn of 8 inches, or 2 inches for the length of one side of an inside turn, and 19 turns per layer, we have from equation 44, Page 122, for the cross section,

$$L_2 = \sqrt{\frac{15973 \times 1}{19 \times 8} + 2^2 - \frac{3 \times 2}{8} + \frac{2.25 \times 1}{64}}$$

10.4, say 10.5 inches for the mean length of one side. The number of radial layers will then be, from equation 46, page 122,

$$n = \frac{(10.5 - 2)}{2 \times .125} + 1$$

34 radial layers.

From equation 47, page 122, the number of turns S' will be,-

$$S' = 19 \times 34 = 646$$ turns, and from equation 45, page 122, the length of a mean turn will be,-

$$L_3 = (4 \times 2) - (6 \times .125) + (4 \times 34 \times .125)$$
$$= 24.25 \text{ inches.}$$

The length of a single layer, if 1/8 inch is allowed between turns, will be,

$$(18 \times .125) + (19 \times .1845) = 5.75 \text{ inches.}$$

Thus there must be provided a space of 11 x 11 inches x 6 inches for winding the resistance, to which, at equidistant points are tapped 20 leads to the contacts on the face of the rheostat.

Design No. 5.

It is required to design a heater for an 18 foot car, to be used on a 500 volt circuit, which under average conditions will maintain the temperature of the car as high as 65° F., when the temperature outside is not lower than 10°F.

From the data on page 130, we find that the radiation required will be (65 - 10) .12 = 66 B.T.U. per second for a 24 ft. car, so we will say 4.5 B.T.U. for the 18 ft. car in this case.

The number of watts will then be 4.5 x 1047 = 4711.5 watts This requires a maximum current of,

$$I_i = \frac{4711.5}{500} = 9.42$$ amperes with no passengers.

Supposing the car to contain 50 passengers, causing a radiation of 50 x .053 = 2.65 B.T.U. per second. This condition requires

that the heater shall transform but,-

$$(4.5 - 2.65) \times 1047 = 1936.95 \text{ watts.}$$

This corresponds to a saving of,-

$$\frac{4711.5 - 1936.95}{746} = 3.7 \text{ H.P.}$$

which may be used in carrying the load when it is greatest, if means of cutting off the current be provided. This gives a saving of about 75 ¢ per hour, for a system using triple expansion, slow speed, condensing engines with coal at $2.00 per ton. The current may be cut down by placing the resistance in four heaters, which can be thrown across the circuit, either in parallel, series parallel, or all in series by means of a simple switch. Each heater must radiate a maximum when all are in parallel of,-

$$\frac{4711.5}{4} = 1177.9 \text{ watts,}$$

and each must pass a current of,

$$\frac{1177.9}{500} = 2.35 \text{ amperes.}$$

This corresponds to a resistance of 212.8 ohms, and the dimensions of the galvanized iron resistance conductor may be calculated precisely as indicated in the previous examples.

Heaters in	parallel,	current	= 2.35	amperes.	Watts	= 4711.5
" "	series-par'l	"	= 1.175	"	"	= 1175.9
" "	series	"	= .588	"	"	= 294.0

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Those desiring to study further the subjects treated in this chapter may consult the following books and articles.-

Carpenter, G.E. A new Rheostat. Trans. A. I. E. E. Vol. IX.

Dawson, P. L'Eclairge Electrique, Vol. IV. p.446.

Kennelly, A.E. Some measurements of the temperature variation in Electrical Resistance of a sample of Copper. Proceedings Elec. Congress, Chicago, 1898.

McElroy, J.F. Car Heating By Electricity. Elec.Wld. Vol. XXVI.

Rennerfelt, G. Formulae for Resistance Coils, Elec.Wld. Vol. 33.

Electric Heat from Isolated Plants, Elec.World, Vol. XXIII.

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PART IV.

THE DESIGN OF DIRECT CURRENT CONSTANT POTENTIAL DYNAMOS.

The purpose of this chapter is to present a systematic method of dynamo design which will represent American practice, and while based primarily upon data derived from machines met with in actual practice, will still include the underlying principles of the subject to such an extent that, by following the methods given, it will be possible for the student to carry out the design of machines of more radical types.

The engineer, when dealing with the design of a dynamo or motor, has before him a far different problem than has the purely theoretical student, as it is his duty to produce a machine, which at a minimum cost, weight and speed, shall have a maximum efficiency and fudurability.

All of those features, however desirable each may be in itself, cannot be secured in any one machine, and therefore a completed design is the result of a series of judicious compromises not comprehended by any general theory which can be stated in definite mathematical terms, as is the case in the solution of a purely mathematical problem.

Before entering upon the calculations of the dimensions of the parts of a generator or motor of given capacity, preliminary assumptions of the values of several fundamental quantities must be made, and upon the judgment exercised in the selection of the values used, depends to a great extent the value of the design.

Having given the capacity of the machine and the

requirements of the service to which it is to be adapted, we must next decide upon:-

1. The type of machine best suited to the requirements of the service it is to render.
2. The speed at which it should be operated.
3. The peripheral velocity of the armature conductors.
4. The magnetic density to be used in the air gap.
5. The proportion of the surface of the armature to be covered by the poles.
6. The permissible rise of temperature of the armature and fields above that of the air.
7. The magnetic materials to be used in the different parts.

When a machine of very small power is desired, a high speed is not objectionable, the bipolar type possesses the advantage of cheap construction, in view of the simplicity of the frame and the compact form of the armature. The high speed machines of larger capacity are now always made of the multipolar type, owing to the ease with which ring armatures may be ventilated and the small mount of material and space required for their frames.

Where high speed machines are not desirable, on account of their high belt velocities, excessive wear and increased cost of maintenance, slow speed, belt driven multipolar types are common.

Where the amount of space occupied becomes a matter of importance, and a high efficiency is desired, the direct connected, multipolar machines are best adapted.

For purposes of classification, direct current machinery may be divided into three classes,-

TABLE XXI.

HIGH SPEED BELTED DYNAMOS.

Capacity in K.W.	Revolutions per minute. minimum	mean	maximum
1	1400	2000	2800
2	1250	1750	2450
3	1170	1500	2200
10	1050	1300	1950
15	960	1160	1770
20	900	1070	1650
30	800	940	1450
40	740	870	1320
60	660	770	1110
80	620	730	975
100	590	675	850
150	540	595	700
200	495	545	625
250	460	500	570
300	435	470	520
350	410	435	475
400	380	405	440
450	360	380	410
500	335	355	380
550	317	330	350
600	300	310	325

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High speed belt driven generators and motors.

Slow speed belt driven generators and motors.

Direct connected generators and motors.

The present practice, as regards the speeds at which these machines should be operated, is embraced within the limits specified in Tables XXI, XXII and XXIII., which are based upon the speeds of the machines of the several classes manufactured in this country at the present time.

No belt driven machines are built in capacities exceeding

TABLE XXII.

LOW SPEED BELTED DYNAMOS.

Capacity in K.W.	Revolutions per minute. minimum	mean	maximum
1	700	1000	1400
2	670	950	1250
5	640	900	1170
10	610	820	1050
15	580	750	960
20	550	710	900
30	510	650	800
40	480	600	740
60	460	555	660
80	450	540	620
100	440	525	590
150	420	485	540
200	395	455	495
250	380	425	460
300	360	400	435
350	345	380	410
400	325	355	380
450	310	340	360
500	295	320	335
550	285	302	317
600	275	287	300

-----o-----

conditions.

Direct connected units are built by several companies with outputs in excess of those given in the tables and as low as 2.5 K.W.

The introduction of the steam turbine into electric station bids fair to bring about an increase in the speed of direct connected units of large capacity, but as yet little data are obtainable on this class of machines.

The relation between the output and the number of poles

TABLE XXIII.

DIRECT CONNECTED DYNAMOS.

Capacity in K. W.	Revolutions per minute minimum	mean	maximum
5	400	500	600
10	340	400	480
15	305	365	415
20	270	340	385
25	250	325	370
30	230	315	355
40	200	295	340
50	175	280	325
70	140	255	310
100	120	235	290
150	110	210	250
200	100	180	230
250	92	156	205
300	86	138	180
350	80	125	160
400	76	115	140
500	70	104	124
600	66	96	112
700	62	92	105
800	60	88	100
1000	59	82	92
1200	58	79	88
1400	56	77	86
1600	55	75	84

----o----

that may well be used in conformity with present practice is given in Table XXIV. It will be understood that these values may be departed from somewhat, if necessary, in order to secure a more desirable proportion of armature core.

The limits within which present practice restricts the peripheral velocity of the conductors on the armature are given in Table XXV, and there is no limitation, relation or connection

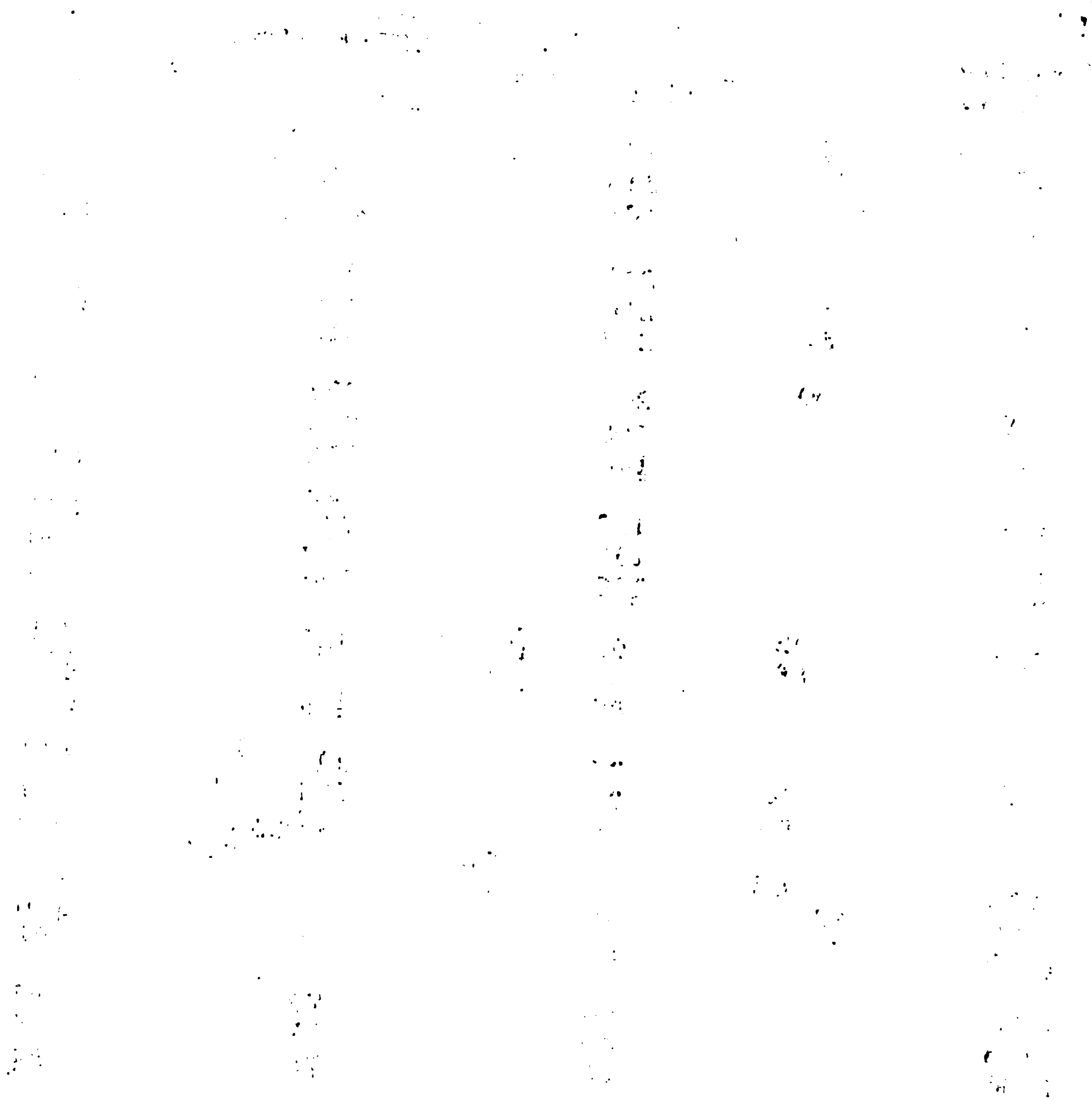

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TABLE XXIV.

RELATION OF CAPACITY TO THE NUMBER OF POLES.

No. of poles.	Class	Output in K.W.
2	High speed belted	0 to 80
4	" " "	0 to 600
6	" " "	60 to 800
4	Low Speed belted	0 to 600
6	" " "	15 to 600
4	Direct Connected	0 to 30
6	" "	15 to 400
8	" "	90 to 400
10	" "	200 to 900
12	" "	300 to 1800
14	" "	600 to 2200
16	" "	800 to 2500

----o----

TABLE XXV.

PERIPHERAL VELOCITIES OF DIRECT CURRENT MACHINES.

	Peripheral Velocity		
Class of dynamo	minimum	mean	maximum
Bipolar high speed belted	2000	3000	3500
Multipolar high speed belted	3500	4000	5500
Multipolar low speed belted	2000	2800	3500
Direct connected	1500	2200	3000

between the output of the machines and the peripheral velocities of their conductors within these limits. In general, it is advisable to select a value near the mean value for the particular class under consideration, as this will give values which will conform closely with those used in the majority of commercial machines.

In selecting the values of the air gap densities, the designer must again be guided by present practice, which gives values found to give the best results under different conditions. Owing to the fact that the magnetic quality of commercial irons

has been greatly improved within the last few years, especially in the introduction of steel castings, machines are now designed with considerably higher flux densities than formerly, and the values given in Table XXVI, although higher than those usually quoted, conform to present usage. In fact, the values given may be regarded as a conservative estimate of the average densities employed, and when the best commercial irons are available, or extreme lightness is desired, even higher densities may be used.

TABLE XXVI.

AVERAGE AIR GAP DENSITIES IN GAUSSES.

Capacity in K. W.	Bipolar Machines Cast iron poles	Bipolar Machines Steel or Wrt. poles	Multipolar Machines. Cast iron poles	Multipolar Machines. Steel or Wrt. poles
1	2700	4200	3400	5000
2	2900	4300	3600	5200
5	3000	4500	3800	5500
10	3400	5000	4300	6300
25	3600	5500	4600	5800
50		5900	5000	7500
				7900
100			5500	7900
200			5800	8500
300			6300	9000
500			6800	9500
1000			7400	10000
2000			8000	11000

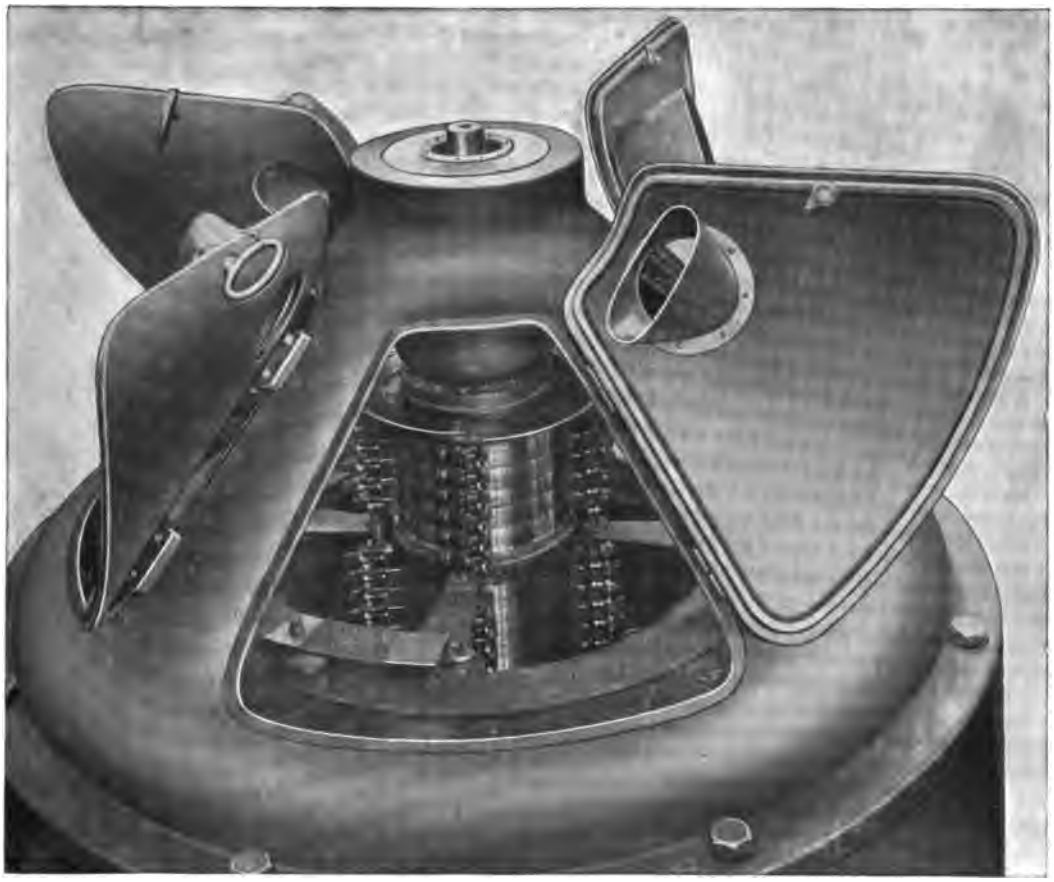
----o----

The values given in Table XXVI refer particularly to the common types of lighting generators, railway generators and motors. Where the machine is to be designed for electrolytic work, values about 25 % less than those given, should be employed. It should be further borne in mind that the densities given in the table refer to the average value of the flux density in the air gap without regard to the bunching of the

lines which occurs when toothed armature cores are used, or the distortion of the field in the air gap which takes place when the machine is loaded.

In deciding upon the average magnetic density to be used in the armature cores, the field cores and the yoke, reference must be had to the data which shows the magnetic quality of the iron to be used in these different parts. In general, the magnetic density in the armature core should be taken at a point below the knee of the curve in the first assumption; this admits of a slight change for adjustment in subsequent assumptions, and since this is the portion of the magnetic circuit in which the flux is reversed, producing a loss by hysteresis, the density should be kept as low as is practicable, since this loss increases approximately with the square of the density.

The magnetic density in the field cores is usually carried to a point slightly above the knee of the curve, well up to the point of saturation, on account of the saving in the amount of copper used in the field winding by decreasing the diameter of the field spools and to insure a better regulation of the machine, due to the fact that above the knee of the curve, the flux increases approximately in proportion to the increased values of H. With high densities in the field cores, the distribution of the flux under conditions of full load is better maintained, owing to the increased reluctance of the magnetic path through the poles. The densities used in the yoke are usually slightly below those in the cores, for the same quality of material, in order to give plenty of metal for stability and solidity in the appearance of the machine.



TURBINE TYPE D. C. GENERATOR.

Quite frequently it is of advantage to use a lower and cheaper grade of iron in the yokes, as the cross section of the higher grade of metals is often so small as to produce a bad appearance to the eye.

Average densities between 9000 and 13000 gausses should therefore be used in the armature cores. Since the number of reversals of the direction of the magnetism per unit time is greater in the armature core of a multipolar machine than in a bipolar having the same speed, there is a greater hysteresis loss in the multipolar armature for the same density and mass of iron. It is therefore evident that with a given per cent. of energy to be dissipated in heat due to hysteresis, lower densities should be used in the multipolar armatures, other conditions being the same; also higher densities may be used in slow speed machines than in the cores of armatures running at higher speeds, the number of poles remaining the same. In accordance with the limits specified above, the general division contained in Table XXVII should be observed.

TABLE XXVII.

MAGNETIC DENSITIES FOR ARMATURE CORES.

Type	Density in Gausses.
Bipolar drum,	3000 to 14000
Multipolar drum (few built)	5000 to 10000
Bipolar ring,	10000 to 15000
High speed multipolar ring	7000 to 13000
Slow speed multipolar ring	10000 to 15000

----o----

If we let,

d = The diameter of the circle described by the middle of the air gap in inches,
L = The effective length of the armature core in inches,
a = The percentage of the active surface of the armature covered by the poles,
V = the peripheral velocity of a point in the middle of the air gap, considering the latter to rotate with the armature.

$$\phi = B \times A = \frac{\pi \times d \times L \times 6.45 \times a}{2\,P} B \qquad (59)$$

$$V = \frac{\pi \times d \times 60 \times n}{12} \qquad (60)$$

and substituting the values of ϕ and n obtained from these expressions in equation 58, we get,

$$E = \frac{B \times V \times (C \times L) \times 6.45 \times 12 \times a}{10^8 \times 60 \times b} \qquad (61)$$

$$= \frac{B \times V \times L' \times 30.5^2 \times a}{10^8 \times 60 \times b} \qquad (62)$$

Where,
L' = the number of active conductors on the armature.

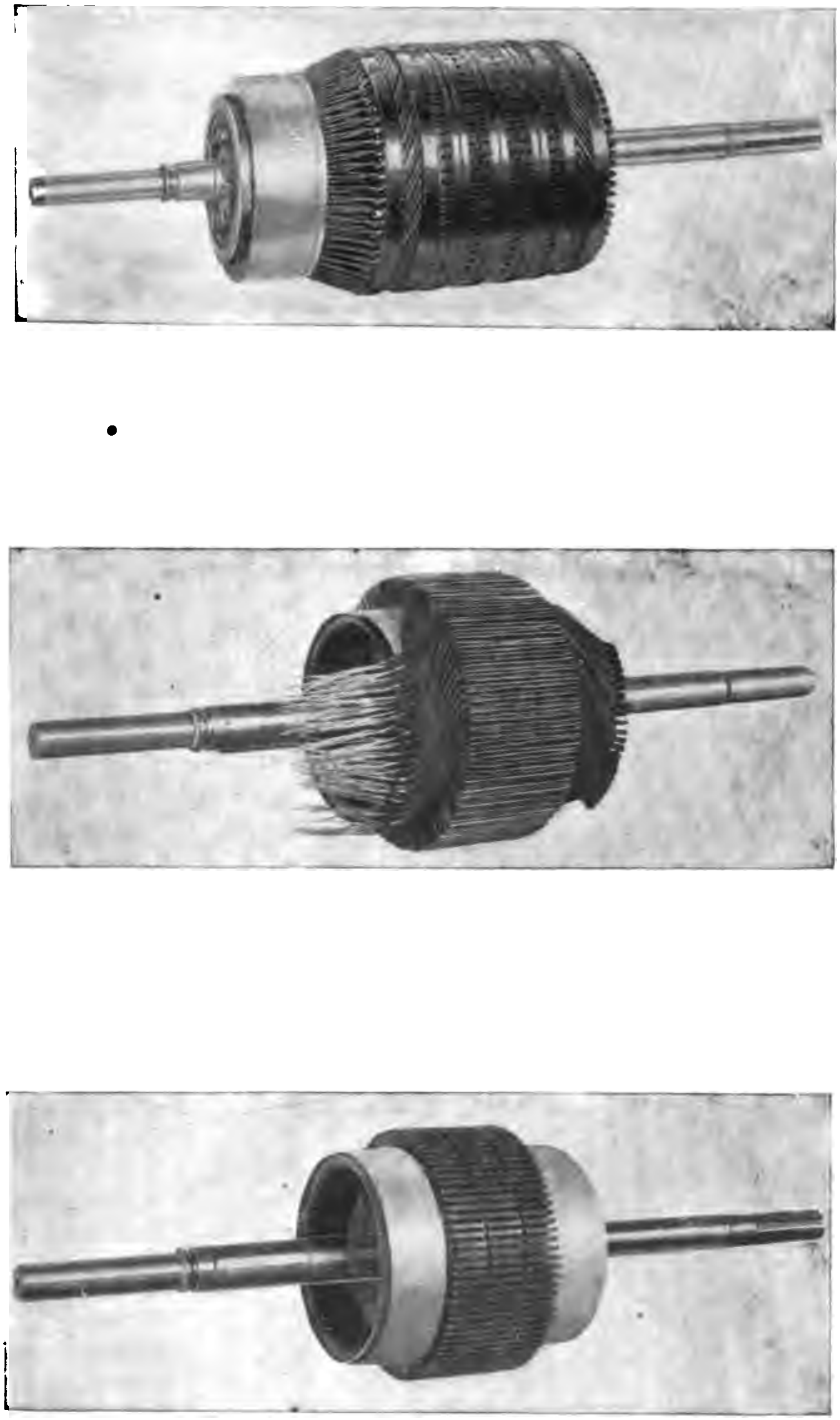
Therefore the number of volts per foot of active conductor on the surface of the armature will be,-

$$e' = \frac{E \times b}{L'} = \frac{B \times V \times 30.5^2 \times a}{10^8 \times 60} \qquad (63)$$

A suitable value taken from Table XXIX and multiplied by the percentage (a) of the surface of the armature covered by the poles will give the value of e' with sufficient exactness for the first approximation.

From the above, it readily follows that the total length of active conductor required for a given armature will be,-

$$L' = \frac{E \times b}{e'} \qquad (64)$$



ARMATURES OF BELTED MACHINES.

Again, since the total E.M.F. developed in the armature full load is,-

$$E = E' + I R_a + I R_s \qquad (65)$$

Where,

E' = The E.M.F. at the terminals.

R_a = The resistance of the armature bwbetween terminals

R_s = The resistance of the series winding.

Since at no load, $E' = E$, the calculations for the armature are made for conditions of no load, and the increase of potential necessary to overcome the ohmic drop due to the resistance of the armature and series winding at full load, is obtained by slightly increasing the value of ϕ, and since the air gap density must for this reason be greater at full load than at no load, for constant brush potential, the no load value of B should be chosen slightly below that which is desired for the full load value.

Having determined the length of active conductor from equation 64, and the winding diameter of the armature from equation 60, the armature winding may be planned.

The full load line current may be calculated from the equation,

$$I = \frac{K.W. \times 1000}{E} \qquad (66)$$

where,

K.W. is the full load rating,
E is the full load terminal voltage.

The armature current at full load is equal to the full load line current plus the current in the shunt field, i_f, whence,

TABLE XXIX.

VOLTS PER FOOT OF ACTIVE CONDUCTOR.

100 % of the Surface of the Armature Covered by the Poles.

Peripheral velocity in ft. per min.		Average Magnetic Density in the Air Gap.					
	3000	4000	5000	6000	7000	8000	9000
1500	.70	..93	1.16	1.40	1.63	1.86	2.10
2000	.93	1.29	1.55	1.86	2.17	2.48	2.79
2500	1.16	1.55	1.94	2.32	2.72	3.10	3.48
3000	1.39	1.86	2.32	2.79	3.26	3.72	4.17
3500	1.63	2.17	2.72	3.24	3 80	4.34	4.89
4000	1.86	2.48	3.10	3.72	4.25	4.96	4.58
4500	2.09	2.79	3.48	4.18	4.88	5.58	6.27
5000	2.32	3.10	3.88	4.64	5.42	6 20	6.26
5500	2.56	3.41	4.26	5.12	5.96	6.82	7.68

----o----

$$I_a = \frac{K.W. \times 1000\ (1 + k)}{E} \qquad (67)$$

Where,

k is the shunt field current expressed in percent of the full load line current. In Table XXIX are given the approximate values of k for generators of various outputs.

From the data given in Table XXVIII, an approximation of the required cross section of the armature conductors can be made, and in general may be taken equal to I' x 700 (m).

If common practice be followed, the active conductor will be placed in two layers on the armature, usually placed in slots.

1. The conductor used must be formed into coils, and then placed on the armature in accordance with a pre-determined plan. The coils for the smaller machines, and those having several turns are usually wound on forms in order to give them a correct and uniform shape and they are then carefully insulated by being bound by tape or other insulating material. Where several wires make up a coil, that is where there is more

than one conductor per coil, the conductors should be insulated from each other by a double or triple cotton insulation.

2. A coil may be composed of a single turn or of many turns, and when more than one turn is used, they may be connected either in series or in parallel (as in the use of stranded conductor) or in series-parallel.

3. Coils are so placed on the armature that one half of each coil is in the outer layer of conductors and the other half in the inner layer. This arrangement is accomplished by giving the end of the coil a peculiar shape, so that they interlock and cross one another at the ends of the armature core. The number of coils into which the armature winding is divided must be made to accord with the "winding" adopted.

4. In deciding upon the winding to be used in any given case, reference should be made to the discussion of armature windings which follows, or to Thompson's, Parshall's, or Arnold's works on armature windings. In general, the simpler forms of winding are to be recommended, particularly a winding easily formed and conveniently repaired.

5. The number of conductors finally adopted, must accord with the requirements of the winding to be used and must at the same time economically fill the active surface of the armature core.

6. The total number of conductors used must be equal to, or be some multiple of, the number of commutator bars.

7. The number of commutator bars or segments per pair of poles, required for direct current dynamos and motors varies from 30 to 100 without regard to the current capacity of the machine.

It is more usual, however, to use between 30 and 80 segments per pair of poles for voltages up to 250 and from 60 to 100 segments per pair of poles for voltages between 250 and 500 volts.

8. The reactance voltage of the coil under commutation should not exceed .75 of the value of the voltage per segment. The calculation of the reactance voltage will be treated later.

9. The value of (a) the percentage of the armature covered by the poles, for bipolar machines should be from 70 to 85 per cent., and for multipolar machines should not be made greater than 70 per cent.

When 80 % of the armature is covered by the poles, the average width of the teeth should be about .3 of the pitch of the teeth, and a part of the laminated pole tips should be cut away to give better regulation. Also if a large percentage of the armature is to be covered by the poles, it will be found better to use a relatively large number of poles, so as to reduce the cross magnetizing effect of the armature ampere turns. If the teeth are made to be .4 of the pitch of the teeth and 65 % of the armature covered by the poles, a multipolar ma-

through the pole tips. It is not advisable to have the densit under the strong pole tip more than twice the average air gap density.

After the total number of conductors (c) on the surface of the armature have been decided upon, the principal dimensions of the armature can be determined by means of the following expressions.

We have,-

$$L = \frac{L' \times 12}{C} \qquad (68)$$

Where,

L = The length of the active portion of a single portion of a conductor in inches, which is equal to the leng in inches of the built up armature core, including from 5 % to 10 % insulation and air spaces between the core discs, besides the ventilating ducts.

In building up an armature core it is customary to make the distance between the end laminae equal to the length of the pole faces. If this is not done, then both L and L' must be multiplied by the ratio of the length of the pole faces to the distance between the bounding laminae.

The radial depth of the armature winding (d'), which in the toothed armature is equal to the depth of the slots, can be determined from a consideration of the arrangement of the conductors on the surface of the armature core, after proper provision has been made for their insulation. In machines of moderate voltage the insulation between conductors in the same coil is limited to double or triple cotton insulation, but in extremely high voltage generators, additional protection is necessary between the coppor conductors and between the coil and the core. Usually the total thickness of insulation from coppe to core is between .06 and .1 inches. In proportioning the conductors and slots of machines in which strip or bar

conductors are to be used, the slots can usually be made of the desired dimensions and the shape of the conductor made to fit, with its insulation.

The total external diameter of the armature is usuequal to,

$$d_1 = d + d' \qquad (69)$$

and the diameter below the teeth is equal to,-

$$d_2 = d - d' \qquad (70)$$

The remaining dimension of the laminae to be determined is the radial depth (D") of the armature core below the slots in inches. This depth may be determined as follows,-

The total flux in the air gap under one pole is equal to the value of Ø in equation 58, page 152.

One half of the flux from one pole must pass through one path of the armature core, so that,-

$$d'' = \frac{Ø}{B'' \times L \times 2 \times f} \qquad (71)$$

where,

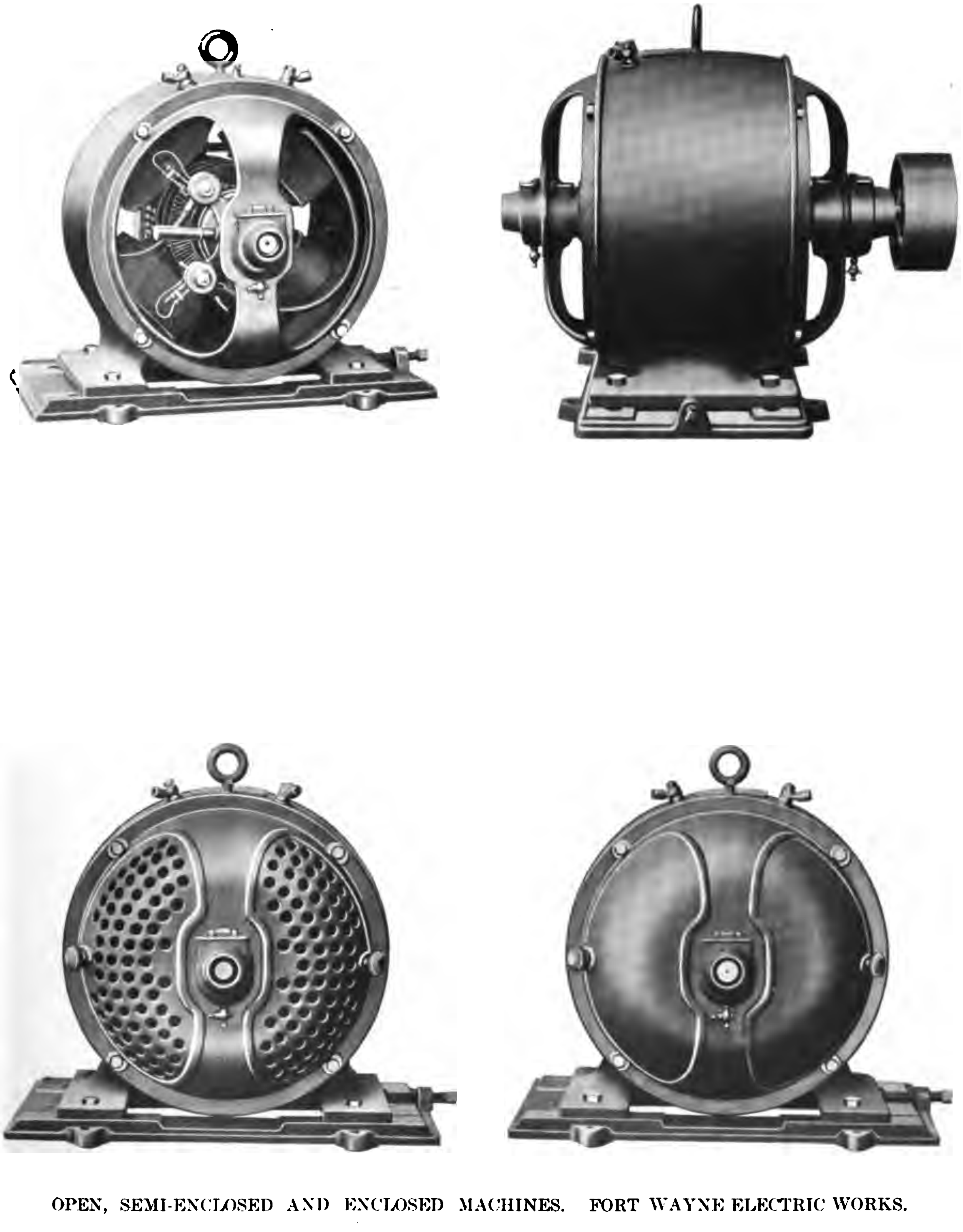
B" = The density in the core below the teeth,
L = The length of the armature core.
f = The percentage of the space between the bounding laminae which is filled with iron.

The value of (f) demdepends upon the thickness of the sheet metal of which the core is made, the insulation placed between the discs and the width of the ventilating ducts.

The sheet iron used varies in thickness from 40 to 15 mils; common practice favoring the use of sheet steel 20 mils thick.

Laminae, when made from the thicker grades of iron, are usually insulated from each other by tissue paper, enamel or varnish.

The thinner grades are often used with no insulation except the oxide coating produced by annealing, though some



OPEN, SEMI-ENCLOSED AND ENCLOSED MACHINES. FORT WAYNE ELECTRIC WORKS.

manufacturers add a coat of japan. For the thicker grades, insulated as above from 90 to 95 per cent. of the cross section of the core is iron, if no ventilating ducts are used. For the medium grades, insulated with enamel, from 85 to 90 per cent. is iron, and for the thin sheets, with an enamel coating, about 80 per cent. and with the oxid alone, from 90 to 95 per cent. of the cross section is iron.

When ventilating ducts are used an additional allowance must be made for them. The ducts should be made as regards number and width, in accordance with data which will be given later.

The dimensions of the core thus far obtained supply sufficient data for the determination of the length of the cross connections and commutator connections of the armature coils. This should be done by making a full size plan drawing of the armature, drawing a set of coils laid off at the proper pitch, as shown in Fig. 49.

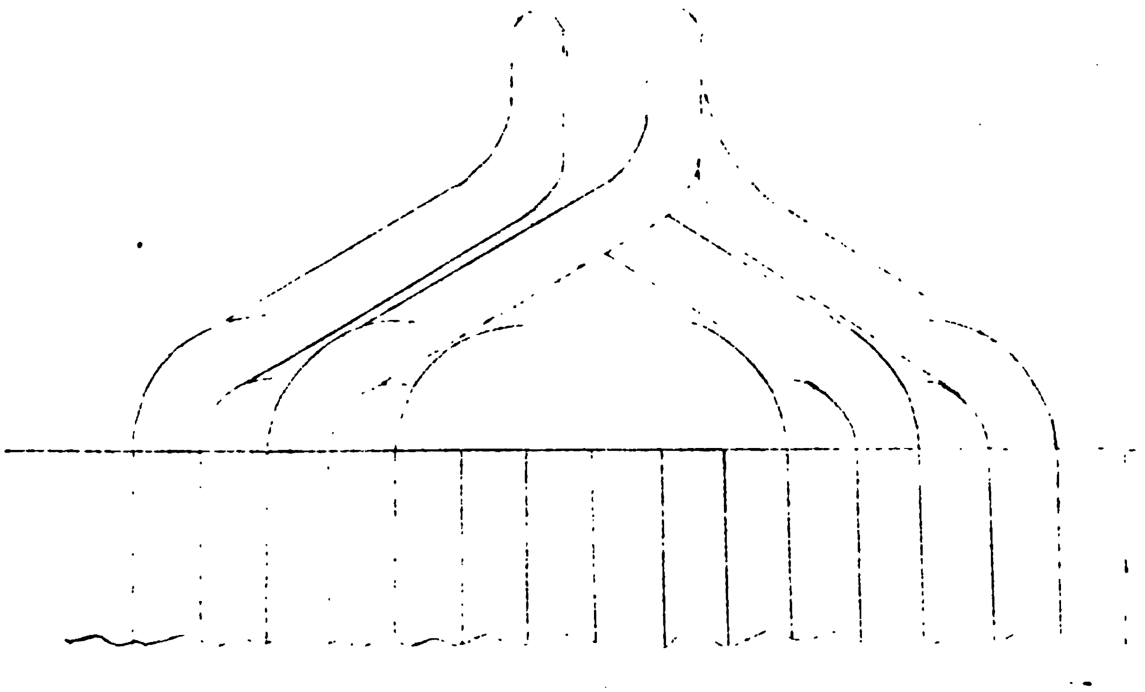


Fig. 49

The figure shows a portion of the projected armature surface, the dimensions being those measured on the circumference, p being the distance between centers of the two sides of one coil. With o as a center, draw the arcs a and a' and draw the diagonal lines tangent to these. Proceed similarly for the left hand side of the coil and where the lines intersect, draw the bend which must be made in the coil. The two ends may be considered to be of the same length and to the length of the wire in each coil must be added that amount sufficient for two leads to the commutator.

Having determined the length of wire in a coil, the total length of wire on the armature may be ascertained, or if desired, the total length between two adjacent brushes, which is the length of one path. The resistance of the armature or the resistance of a path may either one be now calculated.

If $R_{a'}$ be the resistance of one path or circuit through the armature and $L_{a'}$ the length in feet of the conductor in one circuit, the resistance of one circuit, not including the brush contact will be,-

$$R_{a'} = \frac{L_{a'} \times K}{(m)} \qquad (72)$$

and the resistance of the armature as a whole, between terminals, but not including the brush contact resistance will be, if there are b paths in parallel,-

$$R_a = \frac{R_{a'}}{b} \qquad (73)$$

and the I^2R loss in the armature will then be,

$$W_a = I^2R_a \qquad (74)$$

The difference between the potential at the terminals of a plain shunt machine and the developed potential is the drop in the armature winding and the brush contacts. In the case of a compound machine this difference is the drop in the armature winding, the brush contacts and the series or compound winding. This difference between the developed and terminal E.M.F. is usually called the internal drop. In machines of capacity from 1 to 10 K.W. the internal drop varies from 15 to 5 per cent. fr from 10 to 100 K.W. capacity, it varies from 5 to 3 per cent. from 100 to 1000 K.W. capacity, from 3 to 1.5 per cent.

In compound machines the drop should be proportioned between the armature and series windings approximately inversely as the ventilating power of the armature and series field coils.

The rise in temperature of an armature which results from the heating of the armature conductors by the current, is de-
the heating of the
termined as follows:-

If,

I be the total current output of the armature in amp.
S that part of the cylindrical and end surface of the armature exposed to the air, in square inches,
T' the rise in temperature in degrees C. of the armature core due to iron losses.
T'' is the rise in temperature of the armature in degrees C. due to the heating of the armature conductors.
T the allowable rise in temperature of the armature in degrees C. above the air.
K' the radiation coefficient, the value of which varies from .04 to .05, depending upon the conditions of operation and the structure of the armature. In some cases the value of K' may reach .07.

Then,-

$$I^2R_a = K' \times S \times T'' \qquad (75)$$

and therefore,

$$T'' = \frac{I^2R}{K' \times S} \qquad (76)$$

and the sum of T' and T", as already explained, gives the total rise of temperature of the armature above the air.

The maximum allowable current (I_m) which the armature can carry continuously when overloaded, without exceeding the safe temperature rise above the atmosphere, may be determined by substituting the value of the maximum safe temperature rise (T) in equation (83) and solving for the current.

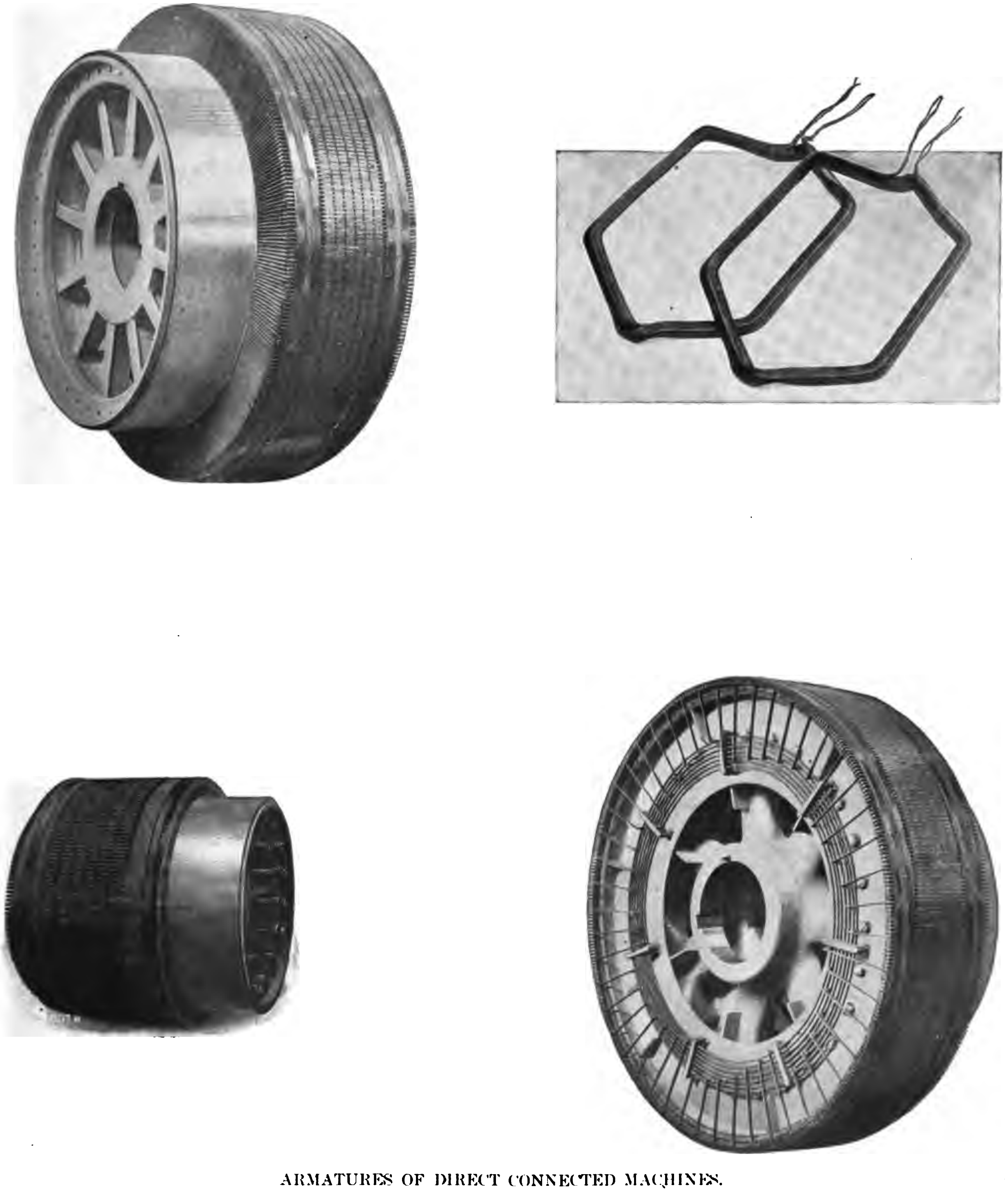
$$I_m = \sqrt{\frac{K' \times S}{R} (T + T')} \qquad (77)$$

For a short period the armature could carry even a greater current than that prepresented by this value, without injury from overheating, and yet only under exceptional circumstances should advantage be taken of this fact, and then only for a very short time. In any case, overloading a dynamo excessively is bad practice, since it must necessarily subject it to dangerous mechanical strains.

TABLE XXX.

DIAMETERS OF BELTED MULTIPOLAR ARMATURES.

Capacity in K. W.	Outside Diam. in inches Min.	Mean	Max.	Ratio of Length to Diam. Min.	Mean	Max.
1	4	7	10	.36	.65	.80
2	5	8	11		.64	
5	6	9	12		.63	
10	8	11	15	.35	.62	.80
20	11	14	19	.34	.59	.78
30	14	17	23	.33	.56	.75
50	17	21	29	.31	.52	.71
75	20	25	35	.28	.47	.67
100	22	29	40	.26	.44	.63
150	26	34	46	.23	.40	.58
200	30	38	51	.22	.38	.55
300	34	44	60	.21	.38	.52
400	38	49	65	.20	.34	.50
500	40	54	66		.32	



ARMATURES OF DIRECT CONNECTED MACHINES.

The dimensions of the armatures of direct connected units, in Table XXXI, follow more definitely established lines. The minimum diameters and the maximum ratios should be used together, and maximum diameters and minimum ratios should be used in determining the best proportions for a given armature. It will be noted that the minimum ratio is nearly a constant for machines of all capacities.

Armatures of the iron-clad and slotted core types, should have the number and dimensions of teeth within the limits given in Tables XXXII and XXXIII. It is found that the best results are obtained by using a large number of narrow slots rather than a small number of wide ones, on account of the excessive eddy currents induced in the pole pieces by the latter and the better regulation which can be obtained by the use of a large number of narrow teeth and slots of considerable depth. The slots are made with their sides parallel, owing to the ease with which the conductors may be placed on the armature core. The teeth are usually notched just below the corners to admit a wooden or fibre wedge, driven into place after the conductors are laid in the slots, to hold them securely in place. These wedges vary in thickness from 1/16" to 1/4", depending upon the diameter of the armature and the width of the slot.

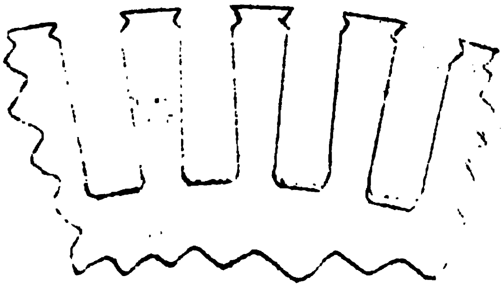


Fig. 50

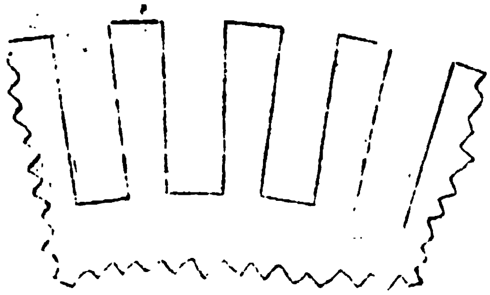


Fig. 51

TABLE XXXII

NUMBER OF ARMATURE SLOTS.

Diameter of armature in inches.	Number of Slots.		
	Minimum	Mean	Maximum
10	25	45	75
20	50	90	135
30	75	125	190
40	95	160	240
60	125	220	325
80	150	260	400
100	175	300	450
120	190	330	470
140	200	350	530

* * *

In Fig. 50 is shown a view of a slot which is commonly used when the slots are punched in the discs, which is the method used by the majority of manufacturers, especially for the larger sizes.

The slot shown in Fig. 51 is the kind made by milling the slots in the core after it is built up. This method is used by a number of manufacturers on armatures up to 16 inches in diameter.

In the case of milled slots, or others in which no provision is made for the wooden wedges, it is customary to turn a number of shallow grooves in the outer surface of the core, varying in depth from 1/32" to 1/16", depending upon the size of the armature.

After the winding is placed in the slots a strip of insulating material is laid over the coils and hard drawn brass wire is wound in the grooves to keep the coils in place. On all armatures, a band of wire, with insulation beneath, should be wound over the end projections of the coils, to

TABLE XXXIII.

DEPTH OF ARMATURE SLOTS.

Diameter of armature in inches.	Depth of Slots in Inches. Minimum	Mean	Maximum.
10	.40	1.00	1.70
20	.60	1.20	1.82
30	.80	1.36	1.90
40	1.00	1.48	1.97
50	1.10	1.57	2.04
60	1.20	1.63	2.10
80	1.30	1.72	2.18
100	1.38	1.72	2.22
140	1.40	1.80	2.30

----o----

Ratio $\dfrac{\text{Depth of Slots}}{\text{Width of Slots}}$ From 2.5 to 4.5

Ratio $\dfrac{\text{Width of Slot}}{\text{Width of tooth}}$ from .75 to 1.5

----o----

prevent their flying outward due to centrifugal force.

COMMUTATORS AND BRUSHES.

The design of the commutator and current collecting devices is of great importance, as the operation of the machine will prove to depend largely upon the skill used in the proportioning of these parts.

The diameter of the commutator should be chosen, such that for a given speed, its peripheral velocity will not exceed 3500 feet per minute; about 2250 feet per minute being the mean peripheral velocity of the commutators built in this country.

On the other hand, the diameter should be such that the segments will present a sufficient surface to the brushes, be able to withstand the wear, and yet not be so wide as to require an excess of copper and brushes of unusual dimensions.

Copper is now universally used in making commutator segments, either rolled, cast or forged segments being used. Rolled segments have proved to be the most satisfactory, due to the uniformity obtained. It is not on the score of its superior conductivity that drawn copper should be used, since the loss due to the resistance of the segment is negligible, but it is of primary importance that the material shall possess the greatest possible uniformity throughout, and freedom from any sort of flaw or inequality. For the same reason, great care should be used in the selection of the mica used as insulation between the segments; it should preferably be just soft enough to wear at the same rate as the copper, but should in no event wear away more slowly, as under such conditions the commutator would present an uneven surface to the brush. Yellow amber mica is best adapted to use in this class of work. The thickness of insulation between the segments and at the ends and below the bars, depends upon the voltage of the machine and may be made in accordance with Table XXXV

The number of segments to be used will be determined largely by the design of the winding, and the voltage of the machine and should be made in accordance with Table XXXVI.

The difference of potential between the commutator segments which is allowable is governed by the reactance voltage of the coil which is short circuited, and varies from 25 volts in small 500 volt armatures to 2 volts in large 110 volt

machines. As stated before, 30 to 60 segments per pair of poles for machines up to 250 volts, and from 60 to 90 segments per pair of poles for machines from 250 to 500 are good values to use. The voltage developed per segment will depend of course upon the number of turns between segments and the flux, and these values also affect the reactance voltage; as will be shown later: the allowable voltage between segments is governed by the reactance voltage which the coil will develop when short circuited by the brush.

TABLE XXXV.

COMMUTATOR INSULATION.

Position of Insulation.	Thickness of insulation in mils. Voltage at Dynamo Terminals. 0 to 300	 400 to 750	 8000 to 3000
Between bars	20 to 30	30 to 40	40 to 60
Below the bars	50 to 100	60 to 120	100 to 200
Ends of bars,	80 to 100	110 to 125	125 to 200

-----o-----

The substructure of commutators is usually made of cast iron, though sometimes of brass or phosphor bronze. The method of clamping the bars in place should receive careful attention, and the pressure should be so applied as to prevent the bar from raising from its position. The commutator should be designed so that maximum wearing quality will be secured for a minimum cost of copper, and so that the brush contact surface may readily be turned up true when the commutater has become worn, without endangering the fastening of the bars.

The commutators of smaller machines are slipped on to and keyed to the shaft, while those of larger machines have their [illegible] up to 250 volts, and [illegible]

pair of poles for machines from [illegible]

use. The voltage developed per [illegible]

upon the number of turns [illegible]

These values also effect the [illegible]

[illegible]

circuit

Between bars 20 [illegible] 3 [illegible]

Below the bars 60 to [illegible] to 5.6

Bars on [illegible] 100 110 to 125 [illegible] to [illegible]

The usual nature of commutator [illegible] mostly of cop[illegible] [illegible], though sometimes of [illegible] of [illegible] of [illegible] the bars in place should [illegible] and the pressure [illegible] applied [illegible] retains them in its position. The commutator should be designed so that the wearing quality will [illegible] part of safety, [illegible] that the [illegible] may be turned up [illegible] when the [illegible] without endangering the fastening of the bars.

The commutators of smaller machines are fixed on [illegible] and [illegible] to the shaft, while those of larger machines have [illegible]

TABLE XXXIV.
DIVISIONS OF COMMUTATORS.

Number of Divisions	Angle of Division	Chord for 1 in. radius	Number of Divisions	Angle of Divisions	Chord for 1 in. radius	Number of Divisions	Angle of Division	Chord for 1 in. radius
1			51	7°03'	.1231	101	3°34'	.0622
2			52	6°55'	.1206	102	3°32'	.0616
3			53	6°47'	.1183	103	3°30'	.0611
4	90°	1.4142	54	6°40'	.1163	104	3°28'	.0605
5	72°	1.1756	55	6°33'	.1142	105	3°26'	.0599
6	60°	1.0000	56	6°26'	.1122	106	3°24'	.0593
7	51°26'	.8678	57	6°19'	.1102	107	3°22'	.0588
8	45°	.7654	58	6°12'	.1082	108	3°20'	.0582
9	40°	.6840	59	6°06'	.1064	109	3°18'	.0576
10	36°	.6180	60	6°	.1047	110	3°16'	.0570
11	32°44'	.5636	61	5°54'	.1029	111	3°15'	.0567
12	30°	.5176	62	5°48'	.1012	112	3°13'	.0561
13	27°42'	.4788	63	5°43'	.0997	113	3°11'	.0555
14	25°43'	.4451	64	5°37'	.0980	114	3°09'	.0550
15	24°	.4158	65	5°32'	.0965	115	3°08'	.0547
16	22°30'	.3902	66	5°27'	.0951	116	3°06'	.0541
17	21°11'	.3676	67	5°22'	.0936	117	3°05'	.0538
18	20°	.3473	68	5°18'	.0924	118	3°03'	.0532
19	18°57'	.3292	69	5°13'	.0910	119	3°02'	.0529
20	18°	.3129	70	5°08'	.0896	120	3°	.0524
21	17°09'	.2982	71	5°04'	.0884	121	2°58'	.0518
22	16°22'	.2847	72	5°	.0872	122	2°57'	.0515
23	15°39'	.2723	73	4°56'	.0861	123	2°56'	.0512
24	15°	.2611	74	4°52'	.0849	124	2°54'	.0506
25	14°24'	.2507	75	4°48'	.0838	125	2°53'	.0503
26	13°51'	.2411	76	4°44'	.0826	126	2°51'	.0497
27	13°20'	.2322	77	4°41'	.0817	127	2°50'	.0494
28	12°51'	.2236	78	4°37'	.0805	128	2°49'	.0491
29	12°25'	.2162	79	4°33'	.0794	129	2°47'	.0486
30	12°	.2091	80	4°30'	.0785	130	2°46'	.0483
31	11°37'	.2024	81	4°27'	.0776	131	2°45'	.0480
32	11°15'	.1960	82	4°23'	.0765	132	2°44'	.0477
33	10°55'	.1902	83	4°20'	.0756	133	2°42'	.0471
34	10°35'	.1844	84	4°17'	.0747	134	2°41'	.0468
35	10°17'	.1792	85	4°14'	.0739	135	2°40'	.0465
36	10°	.1743	86	4°11'	.0730	136	2°39'	.0462
37	9°44'	.1697	87	4°08'	.0721	137	2°38'	.0459
38	9°28'	.1650	88	4°05'	.0712	138	2°36'	.0454
39	9°14'	.1610	89	4°02'	.0704	139	2°35'	.0451
40	9°	.1569	90	4°	.0698	140	2°34'	.0448
41	8°47'	.1532	91	3°57'	.0689	141	2°33'	.0445
42	8°34'	.1495	92	3°55'	.0683	142	2°32'	.0442
43	8°22'	.1459	93	3°52'	.0675	143	2°31'	.0439
44	8°11'	.1427	94	3°50'	.0669	144	2°30'	.0436
45	8°	.1395	95	3°47'	.0660	145	2°29'	.0433
46	7°49'	.1364	96	3°45'	.0654	146	2°28'	.0430
47	7°40'	.1337	97	3°43'	.0647	147	2°27'	.0427
48	7°30'	.1308	98	3°40'	.0640	148	2°26'	.0425
49	7°21'	.1282	99	3°38'	.0634	149	2°25'	.0422
50	7°12'	.1256	100	3°36'	.0628	150	2°24'	.0419

TABLE XXXIV.
DIVISIONS OF COMMUTATORS.

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5	72°	1.1756	55	6°33'	.1142	105	3°26'	.0599
6	60°	1.0000	56	6°26'	.1122	106	3°24'	.0593
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12	30°	.5176	62	5°48'	.1012	112	3°13'	.0561
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15	24°	.4158	65	5°32'	.0965	115	3°08'	.0547
16	22°30'	.3902	66	5°27'	.0951	116	3°06'	.0541
17	21°11'	.3676	67	5°22'	.0936	117	3°05'	.0538
18	20°	.3473	68	5°18'	.0924	118	3°03'	.0532
19	18°57'	.3292	69	5°13'	.0910	119	3°02'	.0529
20	18°	.3129	70	5°08'	.0896	120	3°	.0524
21	17°09'	.2982	71	5°04'	.0884	121	2°58'	.0518
22	16°22'	.2847	72	5°	.0872	122	2°57'	.0515
23	15°39'	.2723	73	4°56'	.0861	123	2°56'	.0512
24	15°	.2611	74	4°52'	.0849	124	2°54'	.0506
25	14°24'	.2507	75	4°48'	.0838	125	2°53'	.0503
26	13°51'	.2411	76	4°44'	.0826	126	2°51'	.0497
27	13°20'	.2322	77	4°41'	.0817	127	2°50'	.0494
28	12°51'	.2236	78	4°37'	.0805	128	2°49'	.0491
29	12°25'	.2162	79	4°33'	.0794	129	2°47'	.0486
30	12°	.2091	80	4°30'	.0785	130	2°46'	.0483
31	11°37'	.2024	81	4°27'	.0776	131	2°45'	.0480
32	11°15'	.1960	82	4°23'	.0765	132	2°44'	.0477
33	10°55'	.1902	83	4°20'	.0756	133	2°42'	.0471
34	10°35'	.1844	84	4°17'	.0747	134	2°41'	.0468
35	10°17'	.1792	85	4°14'	.0739	135	2°40'	.0465
36	10°	.1743	86	4°11'	.0730	136	2°39'	.0462
37	9°44'	.1697	87	4°08'	.0721	137	2°38'	.0459
38	9°28'	.1650	88	4°05'	.0712	138	2°36'	.0454
39	9°14'	.1610	89	4°02'	.0704	139	2°35'	.0451
40	9°	.1569	90	4°	.0698	140	2°34'	.0448
41	8°47'	.1532	91	3°57'	.0689	141	2°33'	.0445
42	8°34'	.1495	92	3°55'	.0683	142	2°32'	.0442
43	8°22'	.1459	93	3°52'	.0675	143	2°31'	.0439
44	8°11'	.1427	94	3°50'	.0669	144	2°30'	.0436
45	8°	.1395	95	3°47'	.0660	145	2°29'	.0433
46	7°49'	.1364	96	3°45'	.0654	146	2°28'	.0430
47	7°40'	.1337	97	3°43'	.0647	147	2°27'	.0427
48	7°30'	.1308	98	3°40'	.0640	148	2°26'	.0425
49	7°21'	.1282	99	3°38'	.0634	149	2°25'	.0422
50	7°12'	.1256	100	3°36'	.0628	150	2°24'	.0419

Number of Divisions	Angle of Division	Chord for in. radius	Number of Divisions	Angle of Division	Chord for 1 in. radius	Number of Divisions	Angle of Division	Chord for 1 in. radius
151	2°23'	.0416	206	1°45'	.0305	261	1°22.75'	.0241
152	2°22'	.0413	207	1°44.5'	.0304	262	1°22.5'	.0240
153	2°21'	.0410	208	1°44'	.0303	263	1°22.25'	.02397
154	2°20'	.0407	209	1°43.5'	.0301	264	1°22'	.0239
155	2°19'	.0404	210	1°42.75'	.0299	265	1°21.5'	.0237
156	2°18'	.0401	211	1°42.5'	.0298	266	1°21'	.0236
157	2°17.5'	.0399	212	1°42'	.0297	267	1°20.75'	.0235
158	2°16'	.0395	213	1°41.5'	.0295	268	1°20.5'	.0234
159	2°15.5'	.0394	214	1°41'	.0294	269	1°20.25'	.02337
160	2°15'	.0393	215	1°40.5'	.0292	270	1°20'.	.0233
161	2°14'	.0390	216	1°40'	.0291	271	1°19.75'	.0232
162	2°13'	.0387	217	1°39.5'	.0289	272	1°19.5'	.0231
163	2°12.5'	.0385	218	1°39'	.0288	273	1°19.25'	.02307
164	2°11.5'	.0382	219	1°38.5'	.0286	274	1°18.75'	.0229
165	2°11'	.0381	220	1°38'	.0285	275	1°18.5'	.0228
166	2°10'	.0378	221	1°37.5'	.0283	276	1°18.25'	.02277
167	2°09.5'	.0376	222	1°37'	.0282	277	1°17.75'	.0226
168	2°09'	.0375	223	1°36.75'	.0281	278	1°17.5'	.0225
169	2°08'	.0372	224	1°36.5'	.0280	279	1°17.25'	.02247
170	2°07'	.0369	225	1°36'	.0279	280	1°17'	.0224
171	2°06.5'	.0367	226	1°35.5'	.0277	281	1°16.75'	.0223
172	2°06'	.0366	227	1°35'	.0276	282	1°16.5'	.0222
173	2°05'	.0363	228	1°34.75'	.0275	283	1°16.25'	.02217
174	2°04'	.0361	229	1°34.25'	.02737	284	1°16'	.0221
175	2°03.5'	.0359	230	1°34'	.0273	285	1°15.75'	.0220
176	2°03'	.0358	231	1°33.5'	.0272	286	1°15.5	.0219
177	2°02'	.0355	232	1°33'	.02705	287	1°15.24'	.02187
178	2°01'	.0353	233	1°32.75'	.0270	288	1°15'	.0218
179	2°00.75'	.0351	234	1°32'	.0268	289	1°14.75'	.0217
180	2°	.0349	235	1°31.75'	.0267	290	1°14.5'	.0216
181	1°59'	.0346	236	1°31.5'	.0266	291	1°14.25'	.02157
182	1°58.5'	.0344	237	1°31.25'	.02657	292	1°14'	.0215
183	1°58'	.0343	238	1°30.75'	.0264	293	1°13.75'	.0214
184	1°57.5'	.0341	239	1°30.5'	.0263	294	1°13.5'	.0213
185	1°56.75'	.0339	240	1°30'	.0262	295	1°13.25'	.02127
186	1°56'	.0337	241	1°29.5'	.0260	296	1°13'	.0212
187	1°55.5'	.0335	242	1°29.25'	.02597	297	1°12.75'	.0211
188	1°54.75'	.0334	243	1°28.75'	.0258	298	1°12.5'	.0210
189	1°54.25'	.03327	244	1°28.50'	.0257	299	1°12.25'	.02097
190	1°53.75'	.0331	245	1°28.25'	.02567	300	1°12'	.0209
191	1°53'	.0329	246	1°27.75'	.0255	301	1°11.75'	.0208
192	1°52.5'	.0327	247	1°27.5'	.0254	302	1°11.5'	.0207
193	1°52'	.0326	248	1°27'	.0253	303	1°11.25'	.02067
194	1°51.25'	.03237	249	1°26.75'	.0252	304	1°11'	.02065
195	1°51'	.0323	250	1°26.5'	.0251	305	1°10.75'	.0206
196	1°50.25'	.03207	251	1°26'	.0250	306	1°10.5'	.0205
197	1°49.5'	.0318	252	1°25.5'	.0248	307	1°10.25'	.02047
198	1°49'	.0317	253	1°25.25'	.02477	308	1°10'	.0204
199	1°48.5'	.0315	254	1°25'	.0247	309	1°09.75'	.0203
200	1°48'	.0314	255	1°24.75'	0246	310	1°09.5'	.0202
201	1°47.5'	.0312	256	1°24.25'	.0245	311	1°09.25'	.02017
202	1°47'	.0311	257	1°24'	.0244	312	1°09'	.0201
203	1°46.5'	.0309	258	1°23.5'	.0242	313	1°08.75'	.0200
204	1°46'	.0308	259	1°23.25'	.02417	314	1°08.5'	.0199
205	1°45.5'	.0306	260	1°23'	.02415	315	1°08.25'	.01987

RULES FOR USING TABLE.

THE CHORD equals the thickness of a division of a commutator of one inch radius, including the mica. The chord also shows the increase per inch in thickness of a commutator bar of the angle given on table.

TO DETERMINE THE DIAMETER OF COMMUTATOR, add thickness of mica desired to the thickness of bar at brush contact edge, divide by CHORD for one inch radius and multiply by two.

TO ASCERTAIN THE THICKNESS OF A COMMUTATOR BAR, multiply the chord of the number of divisions desired by the radius of the commutator to be made, and deduct the thickness of mica.

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supporting parts bolted to the armature spider. The clamping device should be so designed that it will not skew the bars while drawing them into place.

Carbon and graphite brushes are used almost exclusively on direct current, constant potential machines. Owing to the high resistance of the contact of carbon brushes, sparkless operation may be obtained at all loads, without shifting the brushes. The resistance of the contact keeps low the value of the current in the coil which is short circuited by the brush during commutation, and also possesses a certain inertness in combination with the copper commutator which renders the sparking much less destructive than between copper brushes and the segments. They also have the property of burnishing the commutator, giving it a lustrous, refractory surface.

Graphite brushes, while possessing a lower coefficient of friction than carbon, do not impart a polished surface to the commutator, in fact when the brushes are quite soft, there is a tendency in the particles of graphite to adhere to the copper surface, which greatly increases the contact resistance.

Copper brushes are made in two forms, leaf copper and gauze brushes. These possess a much lower contact resistance than

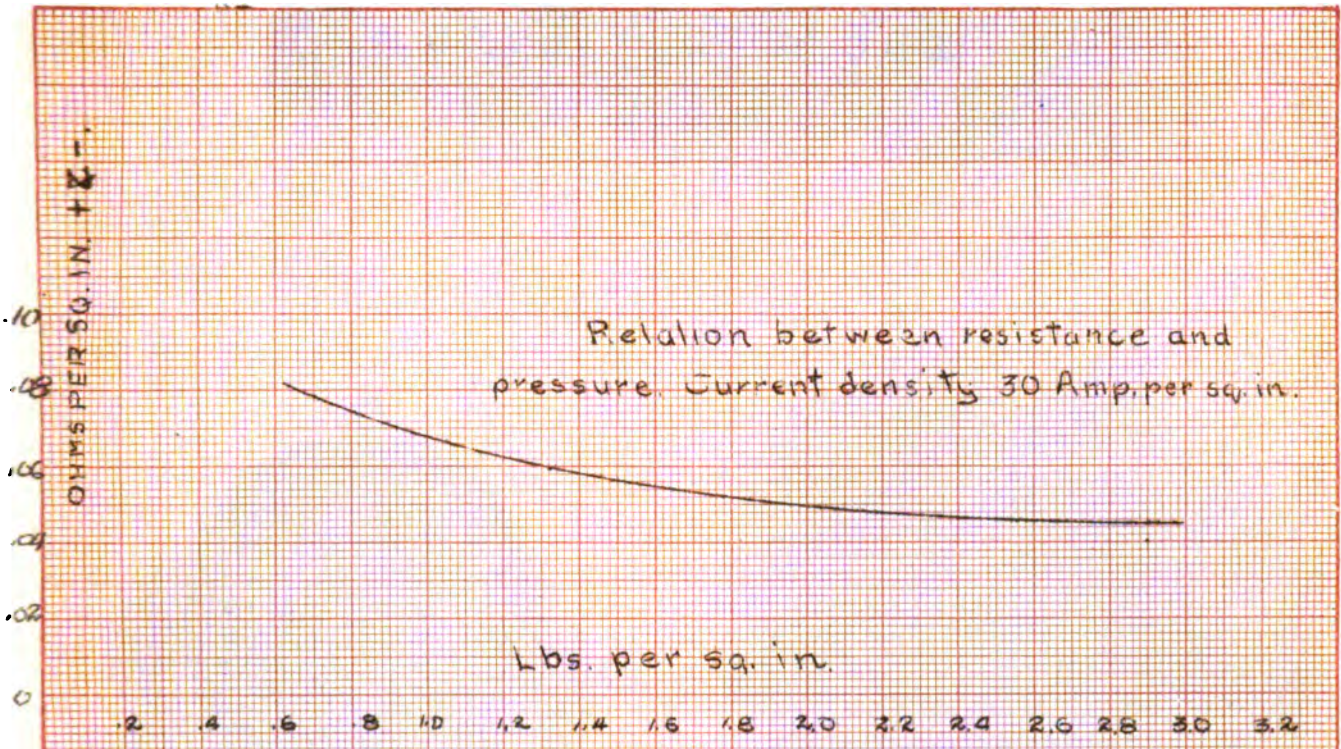
carbon brushes, and are much more destructive to the commutator. They are used only on machines of low voltage and large current capacity.

The required area of brush contact depends upon the current which is to pass through the brush, the assumed value of current density in the contact area. Usually carbon brushes are worked at a current density of from 25 to 40 amperes per square inch of brush contact. Copper gauze brushes may be operated at current densities as high as 100 Amperes per sq. in., and leaf brushes will carry as high as 125 amperes per square inch.

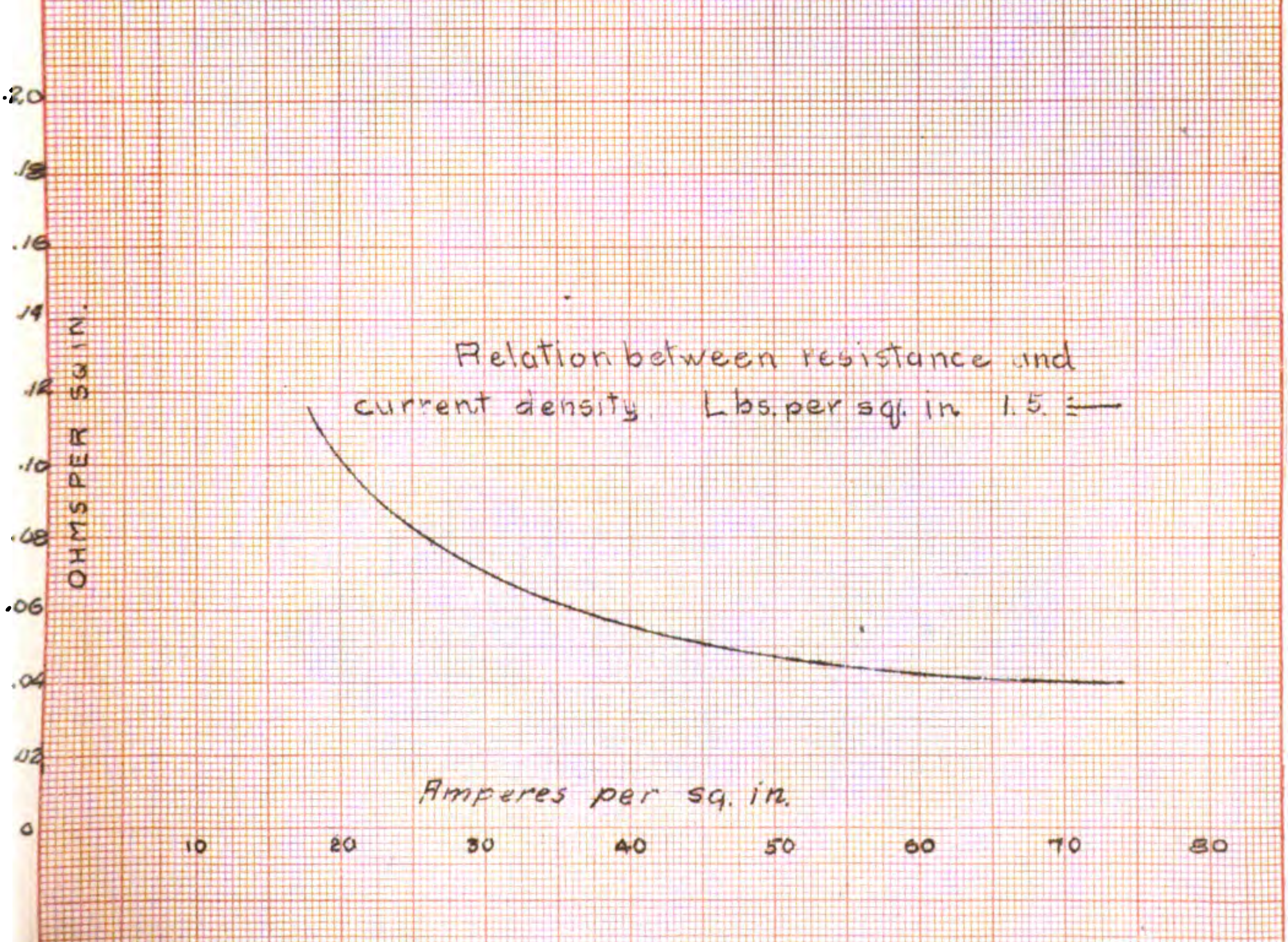
On pages 166 and 167 are given curves of the resistance per square inch of contact area of carbon and graphite brushes for different pressure and current densities. The data given in these curves were obtained by means of a specially designed apparatus illustrated in Plate 17.

A commutator about six inches in diameter was mounted on a heavy shaft, running on ball bearings. The segments of the commutator were short circuited by means of a copper ring. Brushes held in parallel motion brush holders bear on the upper part of the commutator. The shaft is driven by a variable speed motor, through a torsion dynamometer. By taking readings of the dynamometer, with the brushes raised, the bearing friction was determined.

Tests of different grades of carbon and graphite brushes were tested at different speeds, pressures and current densities In the course of the experiments it was found that the resistance of contact under the positive and negative brushes, at the same pressure and current densities is not equal, the positive brush giving the higher resistance of contact. For this reason these curves are plotted giving the resistance of one



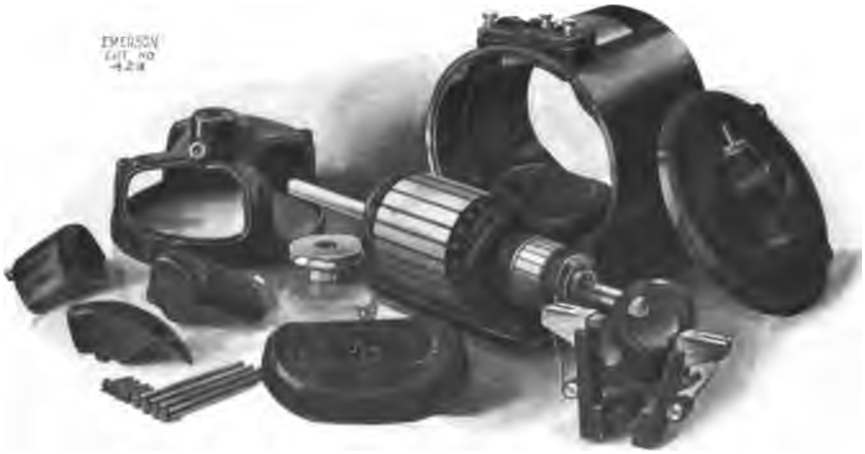
Relation between resistance and pressure. Current density 30 Amp. per sq. in.



Relation between resistance and current density. Lbs. per sq. in. 1.5.

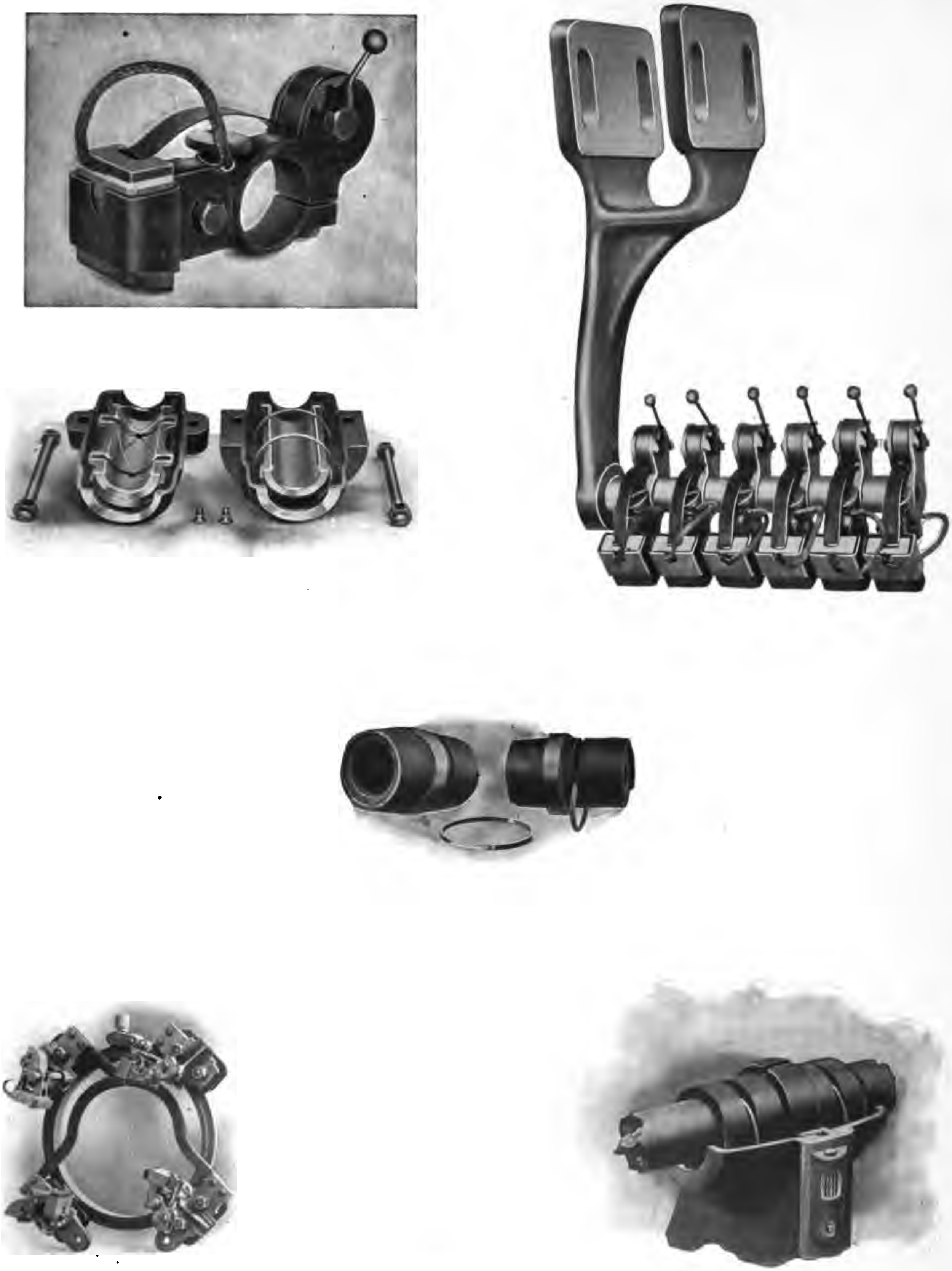
EMERSON.

CROCKER-WHEELER



EMERSON.

SMALL MOTORS.



BRUSH HOLDERS AND BEARINGS.

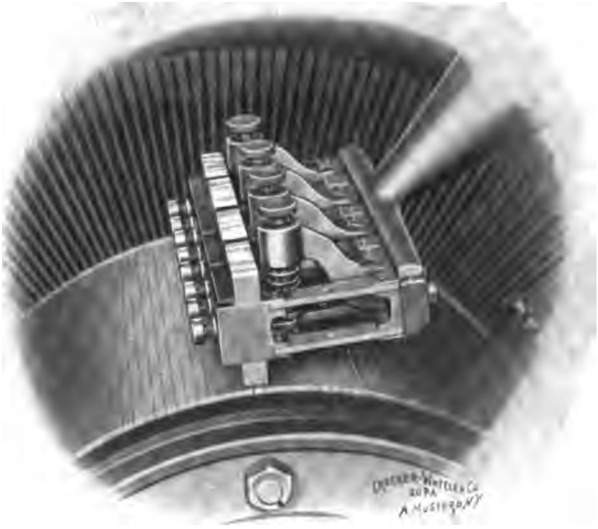
positive and one negative brush in series, that is, the resistances given are for the contacts under one positive and one negative brush, each having an area of one square inch.

Since the friction loss of the brushes increases directly with the pressure, and the resistance of contact decreases with the pressure, there will be for each current density, a most economical pressure to use. Within given limits, the resistance per square inch of carbon brushes, decreases as the current density is increased, and since the friction loss is proportional to the area, we would not expect to get any great increase in economy by using an unusually large brush and a low current density.

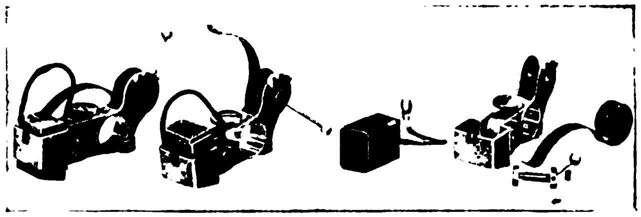
The current which must pass through one brush is always equal to twice the current in one path of the armature. Knowing the area of contact required for one brush, or one set of brushes, a set being all of the brushes bearing on a single commutator segment at any instant, and the number of segments which the brush is to bridge, the width and thickness of the brush is readily determined. The minimum width which can be used is equal to the thickness of one segment plus the insulation between them. Three segments are often covered, and even four may be, if the reactance voltage developed does not become too high under such conditions. Carbon brushes, instead of being left in one large slab, are cut up into a suitable number of pieces, these pieces forming a 'set' of brushes; this admits of the removal of the parts of a set, one at a time, for trimming or renewal, without shutting off the current, and also gives a better adjustment of the pressure over the commutator surface. The space allowed between the brushes of a set should not greatly exceed the end play given the armature in the

FT. WAYNE BRUSH HOLDER.

GENERAL ELECTRIC



CROCKER-WHEELER.



TYPES OF BRUSH HOLDERS.

bearings, so that the commutator will be worn smooth. The end brushes of the set should not be less than one half inch from the ends of the segments.

Knowing the number of brushes required in a set and the thickness of each, as well as the space between each brush and at the ends, the total length of the surface of the commutator may now be determined.

Having determined the dimensions of the commutator and the brushes, the watts dissipated in heat by brush friction and I^2R loss in the brush contacts, and the temperature rise may be calculated.

If we let,

p = the pressure in pounds per square inch with which the brush is pressed upon the commutator.

A_b = the total contact area of all the brushes on the commutator, or area of one set times the number of sets, in square inches.

c = the coefficient of friction.

d = the diameter of the commutator in inches.

Then the watts loss due to friction will be,-

$$W_f = \frac{p \times A_b \times \pi \times d \times c \times 746 \times r.p.m.}{12 \times 33000}$$

Also if we let,-

R''_b = the resistance per sq. in of contact of one negative and one positive brush in series, corresponding to the current density and pressure assumed.

A'_b = the area in sq. in. of the brushes in one set.

Then the resistance of one set of positive and one set of negative brushes in series will be,-

$$R'_b = \frac{R''_b}{A'_b} \qquad (59)$$

and the drop in voltage in themachine due to the resistance of brush contact will be,-

$$E_b = I' \times 2 \times R'_b \qquad (6)$$

where I' is the current in one section of the armature.

The resistancebetween the commutator and the terminals of the machine, not including the resistance of the series winding will be,-

$$R_b = \frac{2R'_b}{b} \qquad (61)$$

where b is the number of paths through the armature in parallel, which is equal to the number of "sets" of brushes.

The watts loss due to the I^2R loss in the contacts will the then be,

$$W_i = R_b \times I_a^2 \qquad (62)$$

where I_a is the total armature current.

If S be the entire radiating surface of the commutator, the brushes and the brush holders, and K' the radiation coefficient, chosen in accordance with the average peripheral velocity of the radiating surface, the temperature rise of the commutator above the air in degrees C. will then be,

$$T = \frac{W_f + W_i}{K' \times S} \qquad (63)$$

In case the temperature rise is found to exceed the allowable value of 60° C. above the air, for continuous operation, the radiating surface should be increased, either by making the commutator hub hollow, to admit of a circulation of air on the inside, or by increasing the outside diameter.

REACTANCE VOLTAGE.

As already stated, the average voltage between commutator segments which is allowable is determined by the value of the

reactance voltage developed in the coil which is short circuited by the brush during commutation. In order to calculate the inductance and reactance voltage of an armature coil, we must first get a practical idea of inductance and understand what takes place in the armature coil during commutation.

A coil has an inductance of one henry when it is situated in a medium of such constant permeability, and is so dimensioned that a current of one ampere sets up a magnetic flux of such magnitude that the product of the number of lines linked with the coil, by the number of turns in the coil is equal to 100,000,000 If the coil has but one turn, then its inductance, expressed in henrys becomes 10^{-8} times the number of lines linked with the turn when one ampere is passing through it. If the coil has t turns, then not only is the magnetomotive force t times as great, but this flux is linked with t turns; hence the product of flux and turns, i.e., the inductance of the coil, is proportional to the square of the number of turns.

The currents in the coils on either side of a positive brush are both flowing toward the brush, and when the coil which is just approaching the brush, has passed from under it, the current will then be flowing through the coil in a direction opposite to that which it had when the coil was approaching the brush. This means that during the time a segment is passing under the brush, the current must become to zero and be set up in the opposite direction; in other words reversed or put through one half of a cycle.

The current which dies away and the one which is set up produce a change in the flux linked with the turns of the coil, the number of lines of force depending upon the number of turns

in the coil andthe area of iron surrounded by the coil.

Experimental results on a number of machines show that an armature coil, under the pole tips, the point of the field in which the coil is commutated, will set up an average of 20 Maxwells per ampere turn per inch of gross length of the armature core, so that if,-

t = the number of turns in one coil between segments which is equal to one half of the number of conductors per coil,

L = The length of the armature core in inches,

The flux set up by unit current in one coil will be,-

$$\phi_c = t \times L \times 20 \qquad (64)$$

As it is usually the case that several segments are covered by one brush, which means that several adjacent coils will be short circuited at the same instant by a single brush, and the lines of force set up by all these coils will be linked by the turns in any one coil.

Further, since parts of two or more coils appear in the same slot, we have the two coils appearing in the same slot short circuited by adjacent brushes at the same instant, and the flux set up by both is linked by the turns of either one of the coils; so that to get the total flux which is linked by a short circuited coil, we must multiply by the number of coils appearing in a slot, and by the length of the core. So that the total flux linked by a coil will be,-

$$\phi_c = n \times t \times L \times 20 \times 2 \qquad (65)$$

where n is the number of coils short circuited by one brush.

The inductance in henrys of one coil will then be,-

$$h = \frac{\phi_c \times t}{10^8} \qquad (66)$$

the time during which a reversal takes place is that

for one segment to pass under a brush, which is equal to,-

$$\text{Time} = \frac{w \times 60}{d \times \pi \times \text{r.p.m.}} \qquad (67)$$

where,

d is the diameter of the commutator in inches,
w is the circumferential width of the brush in in.

and since two reversals are required to make one cycle, we have as the frequency, or the number of cycles per second,-

$$\sim \; = \frac{\text{r.p.m.} \times d \times \pi}{2 \times w \times 60} \qquad (68)$$

the reactance will then be,-

$$r = h \times 2 \times \pi \times \sim \qquad (69)$$

and the reactance voltage will be,-

$$e_r = r \times I' \qquad (70)$$

which should not exceed .75 times the average voltage developed between commutator segments.

In case the value of e_r is found to come too high for a given design, it must be lowered by decreasing the number of turns in series between segments.

----o----

Example of the calculation of the inductance and reactance voltage.

A four pole, 550 volt, 200 K.W. dynamo runs at a speed of 750 r.p.m., the armature has a four circuit, single winding, arranged in 12 0 slots, with four conductors per slot. The commutator is 20 inches and it has 240 segments. The brushes are .75 inches thick; segments .26 inches in width. What is the reactance voltage of a coil during commutation? L = 10 inches.

----o----

[illegible]

(109)

[illegible] and 16 times the average [illegible]

[illegible] of r_p is found to some too high [illegible] analysis, it must be remembered [illegible] in a few hours [illegible]

[illegible]

It is seen that since the brush width is equal to the width of three segments, the maximum number of coils short circuited at one time will be three. Since there are 4 x 120 or 480 conductors, 240 turns and 240 commutator segments, there will be one turn per segment.

The current in one section of the carmature will be,

$$I' = \frac{200 \times 1000}{4 \times 550}$$

$= 91$ amperes; and the total flux linked with one coil will be, from equation 65, page 174,-

$$\phi_c = 3 \times 1 \times 2 \times 10 \times 20$$

1200 maxwells, the flux for unit current which is in accordance with our definition of the henry, the unit of self induction.

The inductance will then be, from equation 66, page 174,

$$h = \frac{1200 \times 1}{10^8}$$

$$= .000012 \text{ henrys.}$$

The frequency is, by equation68, page 175,

$$\sim = \frac{750 \times \pi \times 20}{2 \times .75 \times 60}$$

$$= 530 \text{ cycles per second.}$$

From equation 69, page 175, the reactance will be,-

$$r = 2 \times \pi \times 530 \times .000012$$

$$= .040 \text{ ohms.}$$

From equation 70, page 175 the reactance voltage is,-

$$e_r = \frac{550 \times 4}{240}$$ = 9.2 volts, which

shows that the reactance voltage is within the specified limits.

DYNAMO SHAFTS AND BEARINGS.

In designing shafts for generators and motors, recourse may be had to the standard works on machine design or to the following formulae, which are based on the usual methods given for machine design, with special modifications to meet the requirements of electrical machinery. On account of the magnetic pull which comes upon a shaft which is slightly out of center of the poles, the shafts of dynamos are usually made somewhat larger than for other machines of the same capacity, such as engines, turbines, etc. For the same reason, the bearings should be very strong and rigid, and they should have ample wearing surface, in order that the armature shall not become materially displaced, with represpect to the poles.

The diameter of the portion of a shaft within the core, when made of steel, may be found from the following expression,-

$$d_c = K_1 \sqrt[4]{\frac{W}{N}} \qquad (71)$$

where,

d_c is the diameter of the core portion of the shaft in inches.

W is the output of the machine in watts.

N is the speed in revolutions per minute.

K_1 is a constant depending upon the output of the machine as given in Table XXXVI.

The formula for the length of the bearing is,-

$$L_b = K_3 \times d_b \times N \qquad (72)$$

where,

L_b is the length of the bearing in inches, meaning the length of the wearing portion of the bearing.

d_b is the diameter of the shaft in the bearing

K_3 a constant depending upon the kind of armature and the output of the machine as given in Table XXXVI.

TABLE XXXVI.

SHAFT AND BEARING CONSTANTS.

Capacity in K.W.	Values of Constants.		
	K_1	K_2 High Speed	K_3 Low Speed.
1	1.0	.075	.100
5	1.1	.100	.150
10	1.2	.115	.175
50	1.3	.125	.200
100	1.4	.150	.225
200	1.5	.165	.240
500	1.6	.175	.250
1000	1.7	.200	.275
2000	1.8	.225	.300

----o----

ARMATURE WINDINGS.

Although a large number of different forms of armature windings have been devised, practice has narrowed down to a few simple styles of winding.

Ring windings, in which each conductor found a return circuit through the spider, are no longer used and will not be considered. Practically all windings now used are of the drum type, in which both sides of the coil lie on the armature surface and are active in the generation of energy.

Drum armature windings may be made either single, double, triple, etc. If a winding is so arranged that one commutator bar under a brush carries all of the current from one side of the armature to that brush, then the winding is said to be single. If, however, two bars convey the current from one side to the brush, the winding is said to be double; if three bars convey this current, it is a triple winding. Triple and quadruple windings are not infrequent ion machines of great

current capacity.

All drum windings for the armatures of multipolar machines are divided into two general classes: First, lap-wound, a development of which is shown in Fig. 52. Second, wave-wound, similarly shown in Fig. 53. These windings are sometimes referred to as multiple and series-windings, respectively. Their true distinction, however, lies in the fact that in the first case the turns of wire lap back each turn, while in the other case each turn progresses from pole to pole. The conductors under each pole have a definite direction with reference to their generated electromotive force, and the first point of consideration is to connect the conductors so that the electromotive forces add. An inspection of the various diagrams will quickly show that if the electromotive force be followed down a wire which at any instant is under a north pole, that wire must be connected to one under a south pole. From an electrical point of view, this need not be the next adjacent pole. It may be any south pole of the field. For reasons of a geometrical nature, however, and because it will require a minimum length of wire, the conductors lying under adjacent poles connected together, and as far as possible those lying under similar portions of the poles will be joined since this procedure will obviously yield a greater electromotive force.

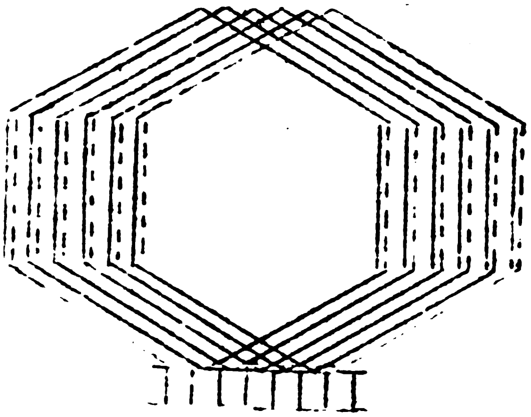


Figure 52

The distance between the centers of two adjacent poles is

the pole pitch and the distance between the two conductors of the same coil is the throw of the coil. These are usually expressed in terms of armature slots instead of degrees or inches.

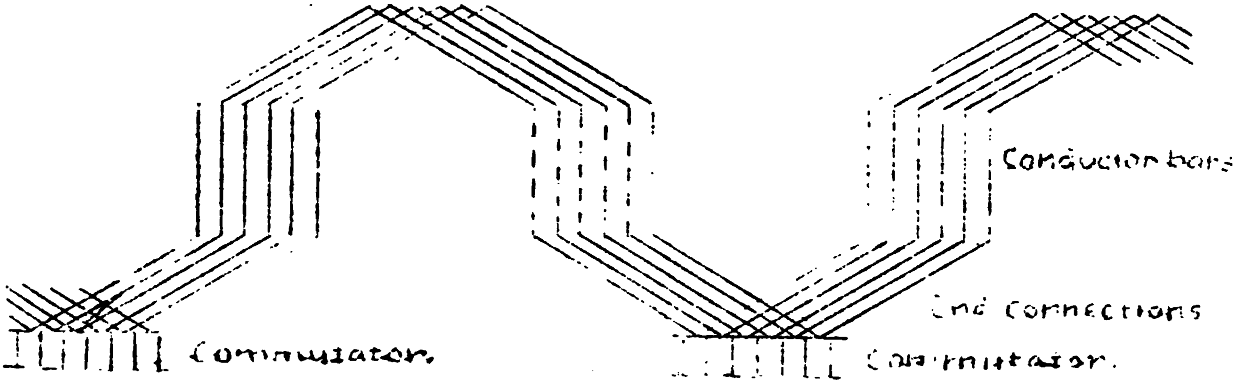


Figure 53.

In as much as there may be several coils in a slot, the pitch can not well be measured in slots; and as there may be one or more turns in a coil, it is not well to attempt to measure the pitch of the coils in conductors. Obviously, the number of turns in a single coil does not affect the pitch of the coil. It will be found convenient to measure pitch in coils, or better in half coils. Suppose we were to take a section of an armature perpendicular to the shaft; we would cut through each coil twice, and if we for the time consider each side of a coil, or better each half of a coil as one conductor, provided all the turns in one coil are in series, and treat them as such in drawing the diagram, little difficulty will be experienced.

In lap windings the throw of the armature coils can never equal the throw of the end connections. It is usually made one more or one less. In wave windings these throws may be

equal, but are not necessarily so. That is, the number of slots enclosed by a coil is not necessarily equal to the number of slots lying between this coil and the coil to which it is connected at the commutator. In any case, however, the throw of the coil, plus the throw of the end connection must be very closely equal to two times the pole pitch. In practice it is customary to make the throw of the coil equal to or slightly less than the threw of the end connection. When a coil is composed of several turns, it is obvious that this construction requires less wire than if the throw of the coil were slightly greater than the throw of the end connection.

If the throw of the coils is very much less than the pitch, it is quite obvious that there will be periods when both the condustors of one coil will lie under the influence of one pole which, of course, would mean periods of zero electromotive force in that coil. The threw is therefore usually made but slightly less than the pitch since this requires less wire, and also

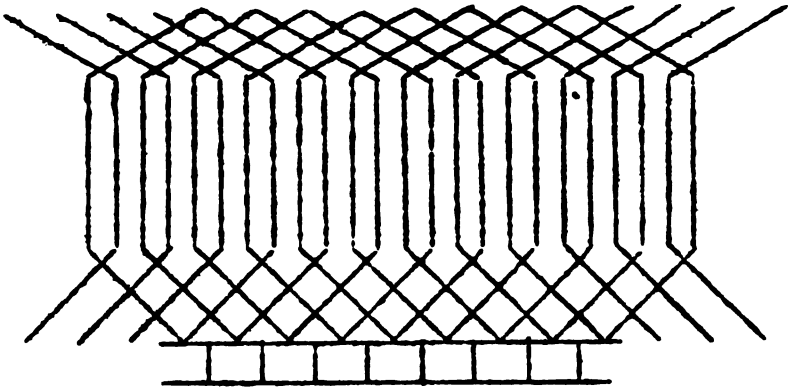


Figure 54.

because it quite often happens that a throw exactly equal to the pitch would encounter a fraction of a slot, or for various other

geometrical reasons The remainder of the problem of winding an armature is one of geometry. All armatures are wound for one or two conditions, viz., low voltage and large current, or high voltage and low current. For the first condition the armature must be provided with a large number of paths in parallel, and for the second a very small number of parallel paths with a correspondingly large number of series conductors. Commercially this is accomplished by two types of winding; first, the lap winding having a commutator pitch of adjacent commutator bars and therefore having parallel paths equal to the number of poles; second, the two-circuit wave winding having two parallel paths.

LAP WINDING.- The following refers to lap windings having as many paths in parallel as there are poles, though there may be two, three, four, or more times this number. In these other cases wide brushes are necessary, which give troublesome contacts.

Each pole represents in a way a complete generator in itself. There is always a brush for each pole and all the brushes of like sign are joined to form the two terminals of the machine

If each slot accommodates two coils, i.e., one side each of two coils, this winding may be constructed on an armature of any number of slots, but if each slot holds but one conductor, as shown in Fig. 54, the number of slots must be even. For if any armature be constructed with two conductors per slot, as shown in Plate 19 and succeeding plates, then to change it to one conductor per slot would mean to provide twice as many slots, and whether the armature in the first place had an odd or an even number of slots, twice the number would always be an even number.

Plates 19 and 20 show standard lap windings for a

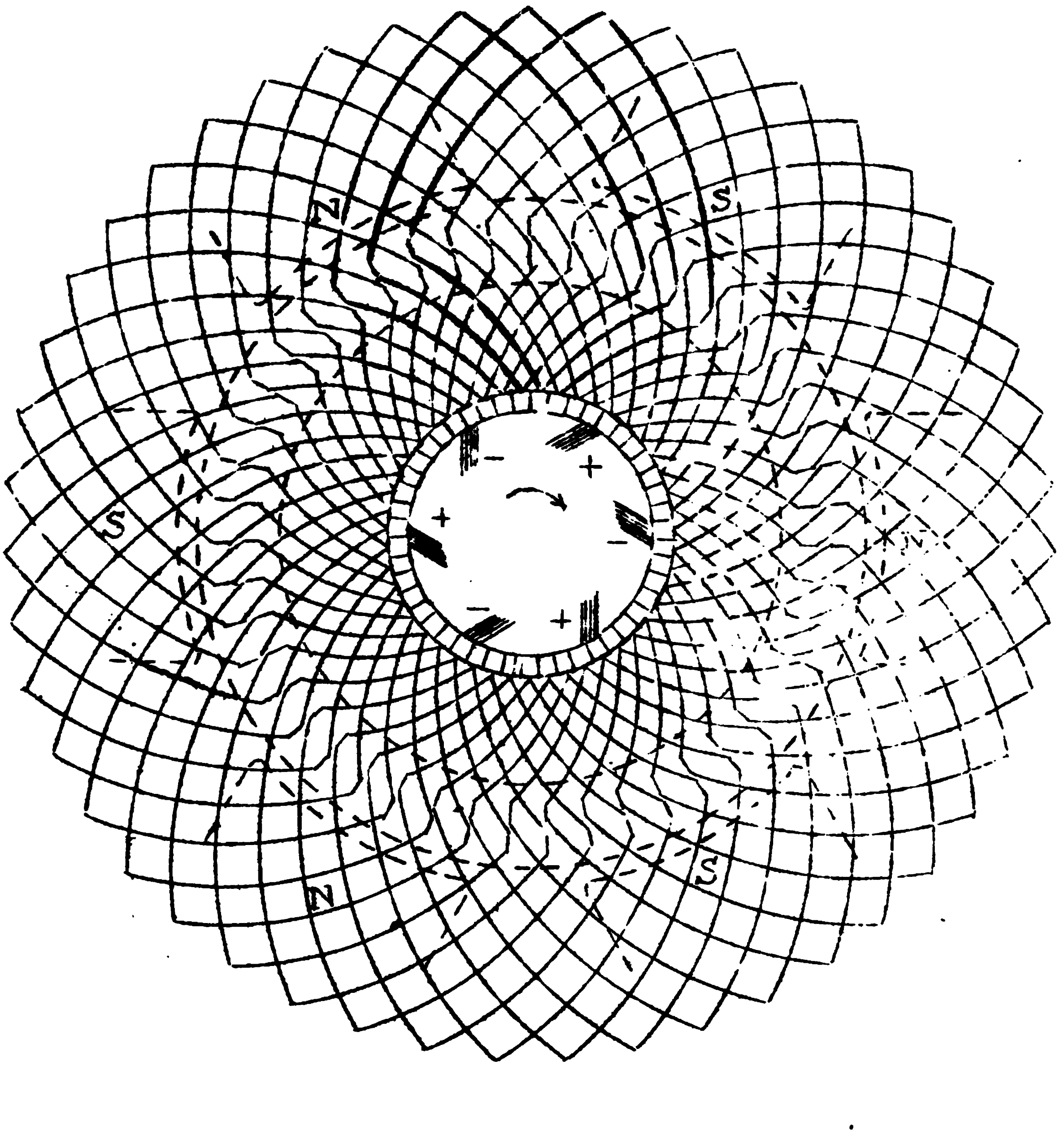
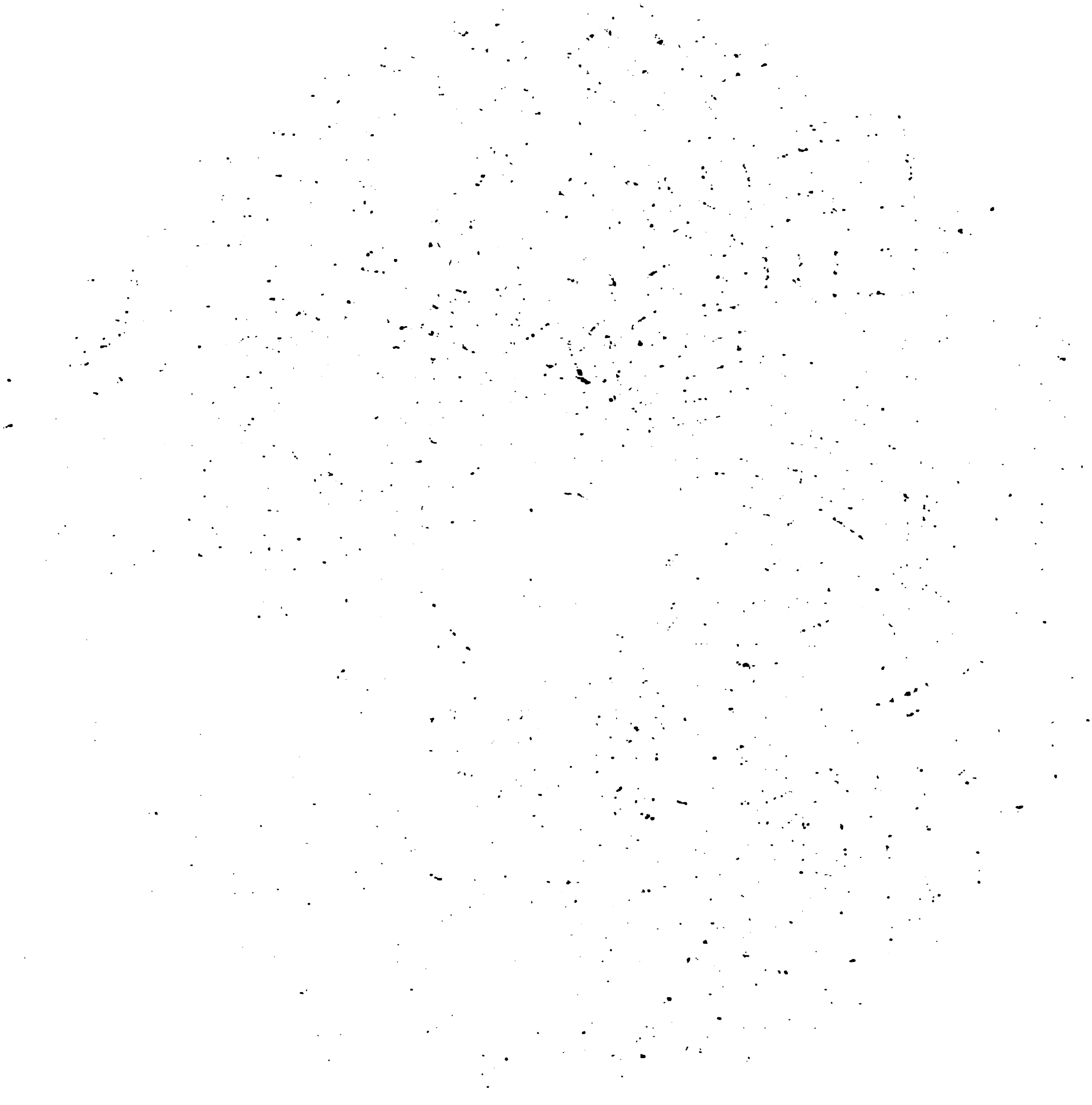


PLATE 19.

Lap Winding. Multiple Circuit, Progressive, Six Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils per Slot.



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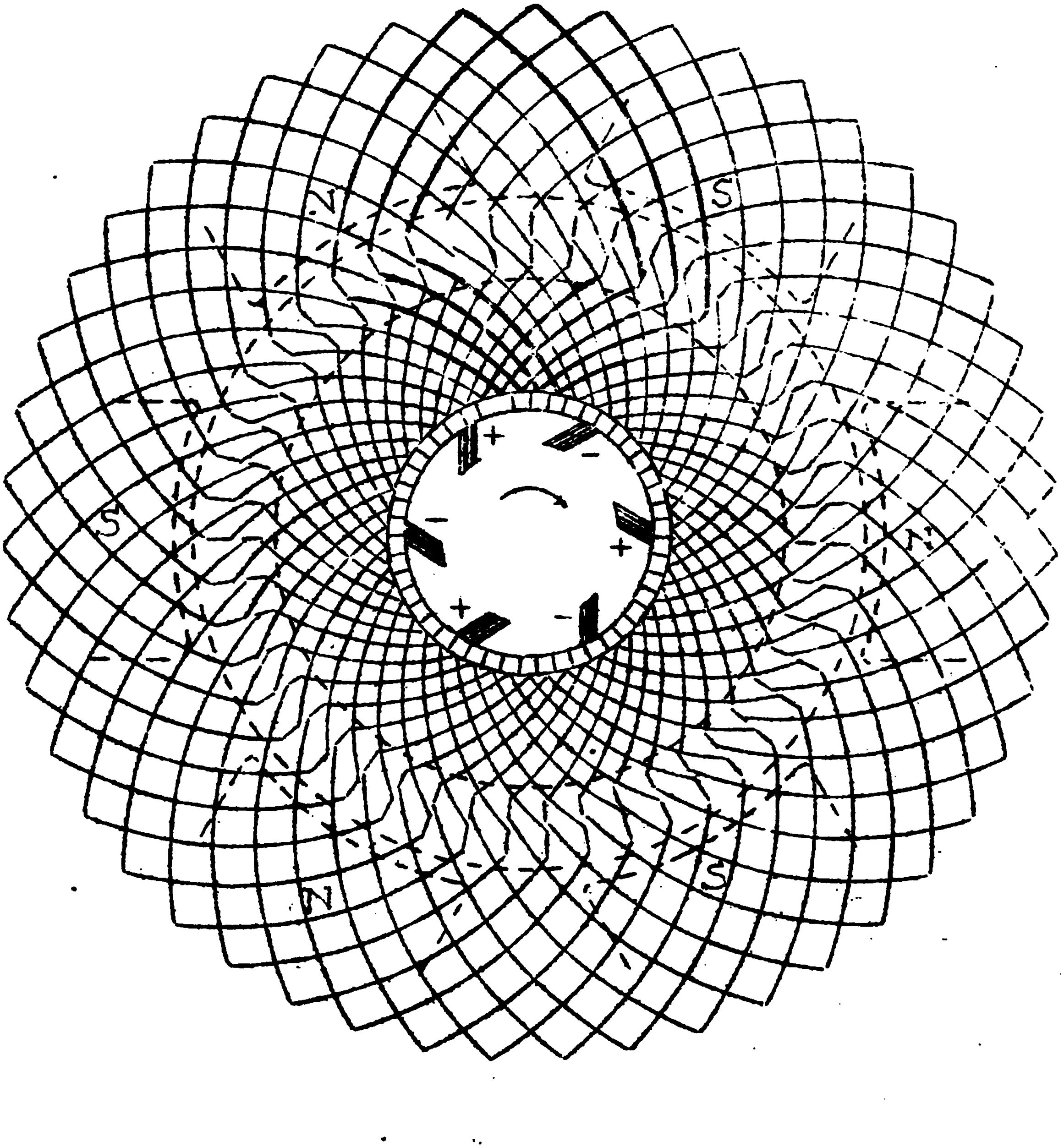
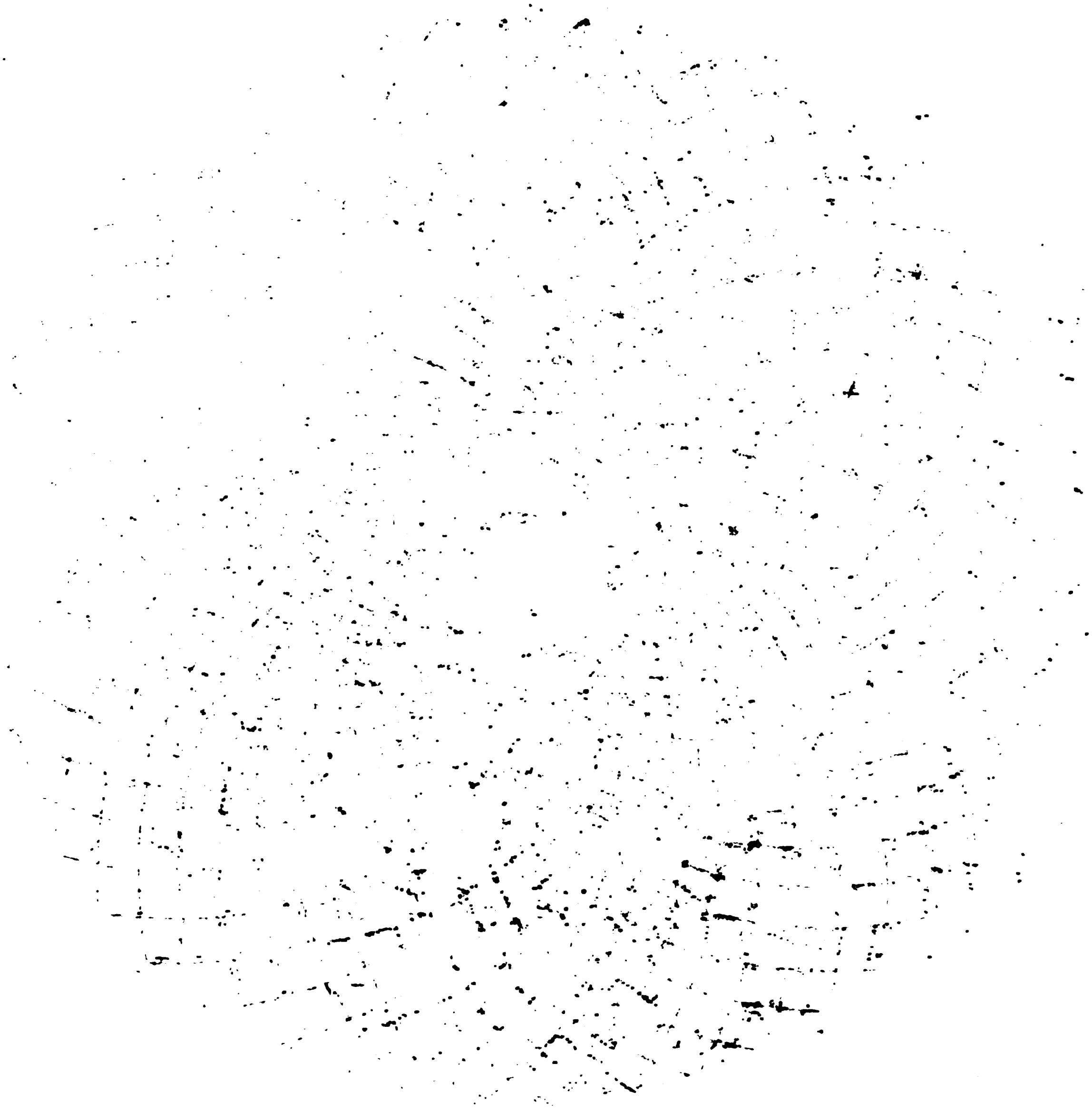


PLATE 20.

Lap Winding. Multiple Circuit, Retrogressive, Six Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils Per Slot.



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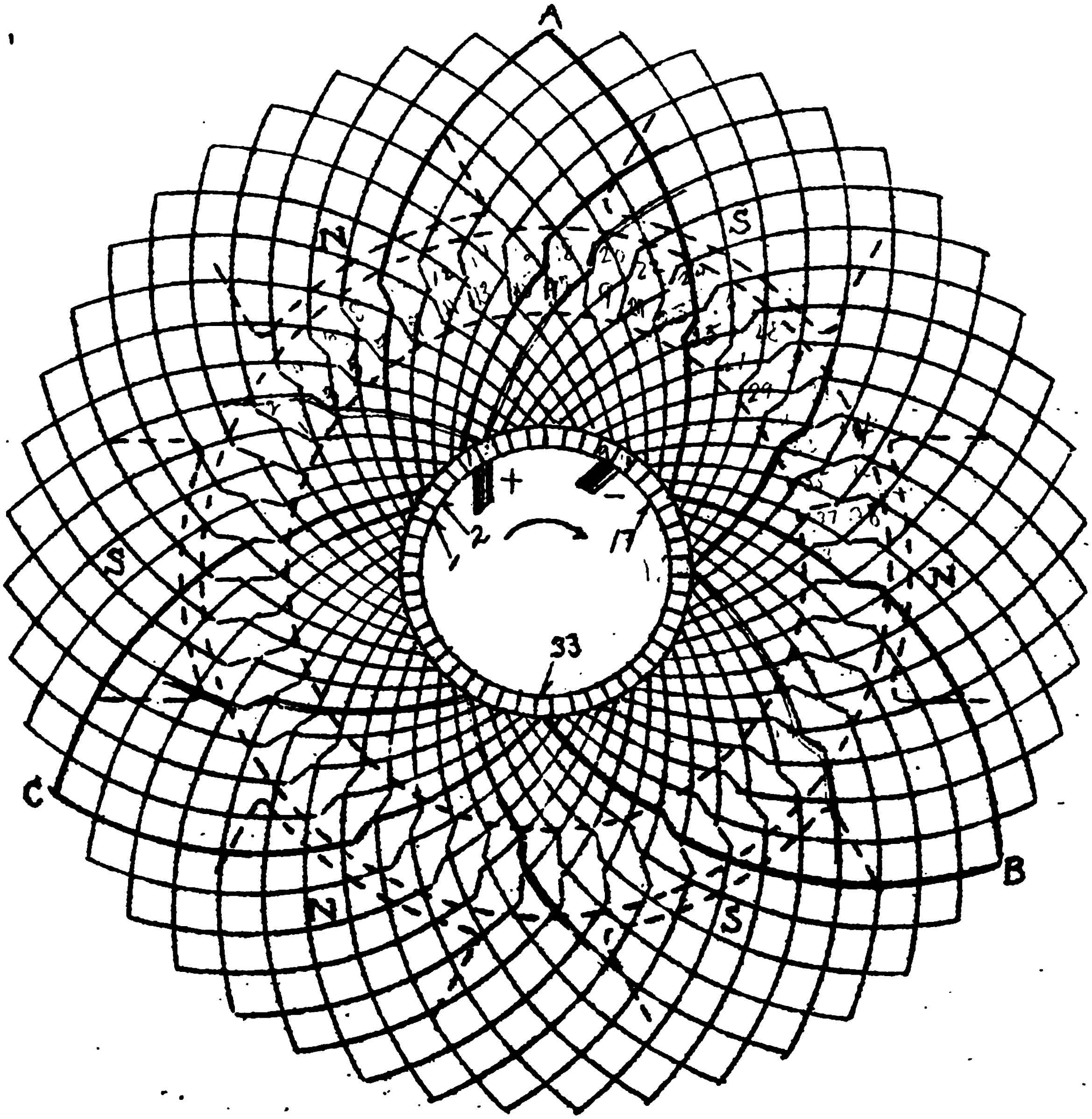

PLATE 21.

Wave Winding. Two-Circuit, Progressive, Six Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils Per Slot.

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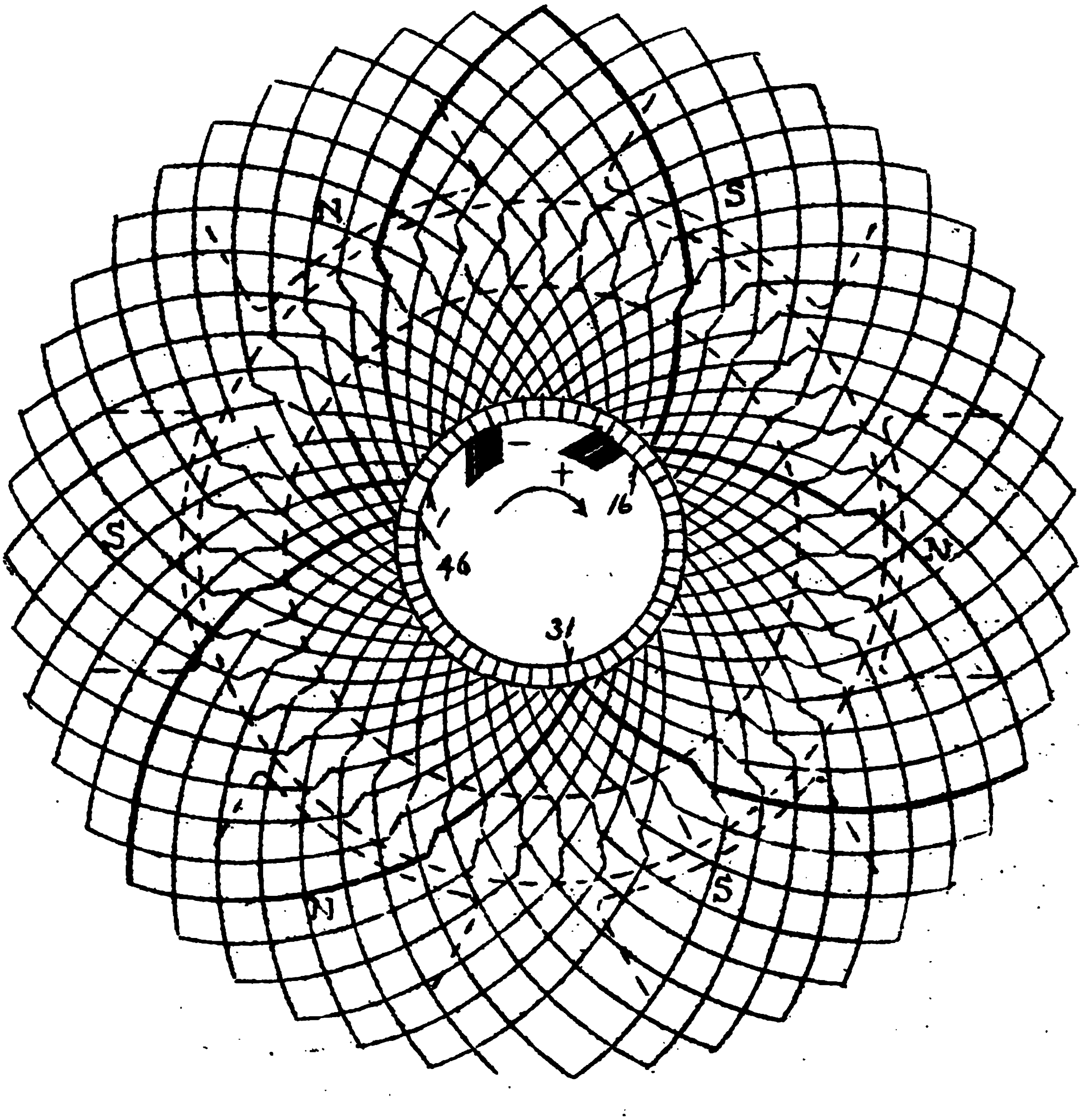

PLATE 22.

Wave Winding. Four Circuits, Retrogressive, Six Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils per Slot.

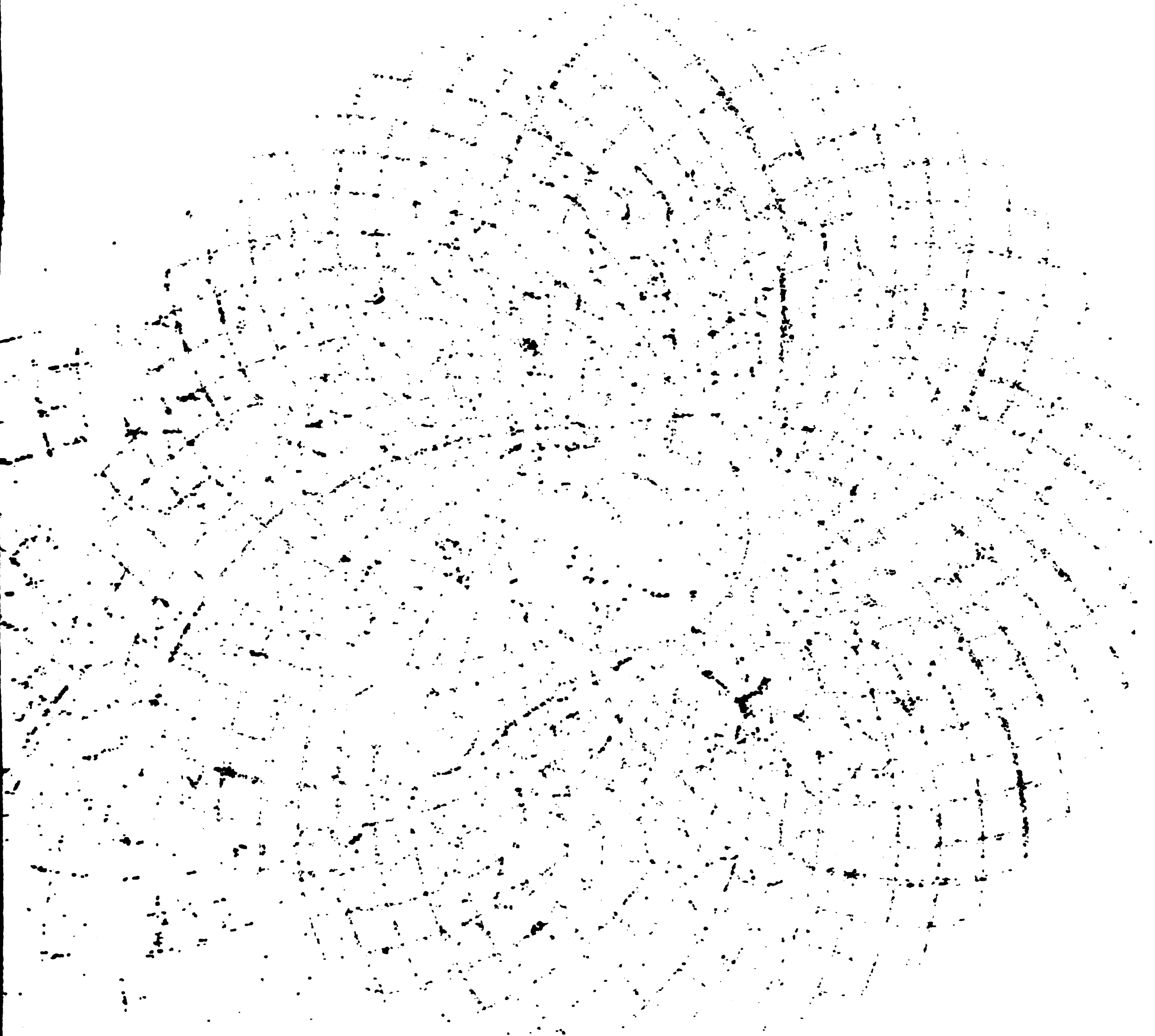

PLATE 26.

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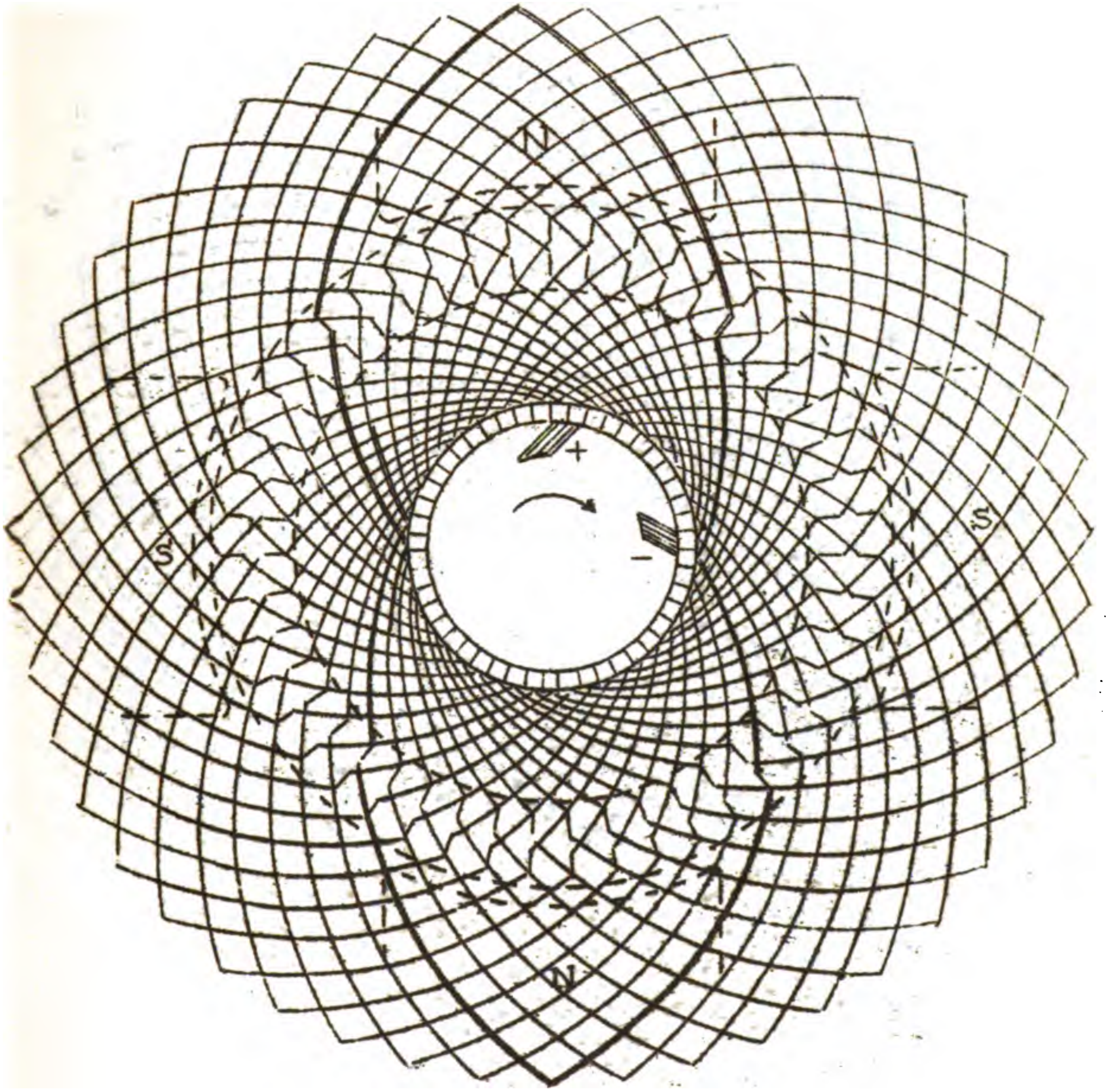

PLATE 25.

Wave Winding. Two-Circuit, Progressive, Four Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils Per Slot.

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[illegible]

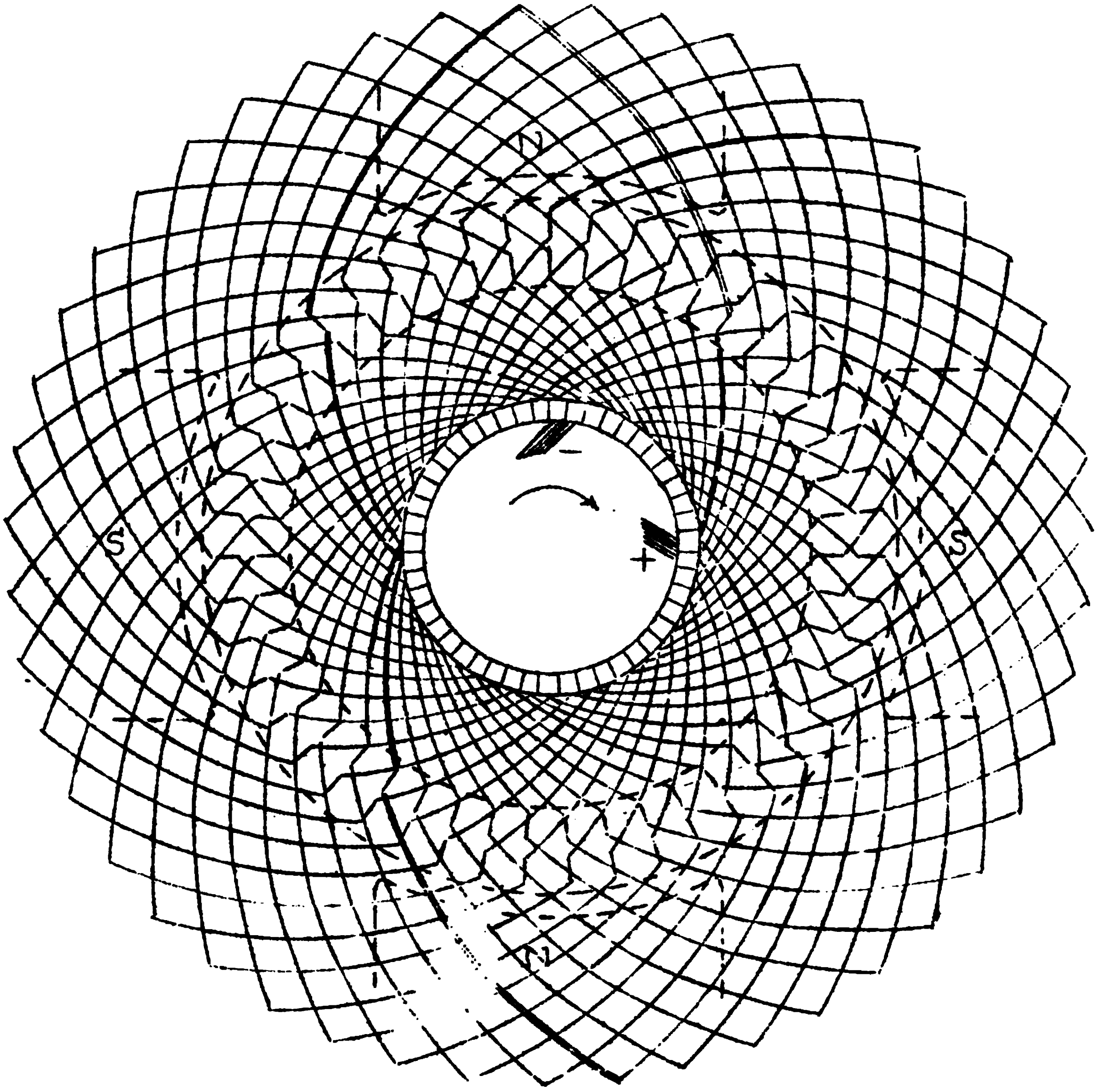
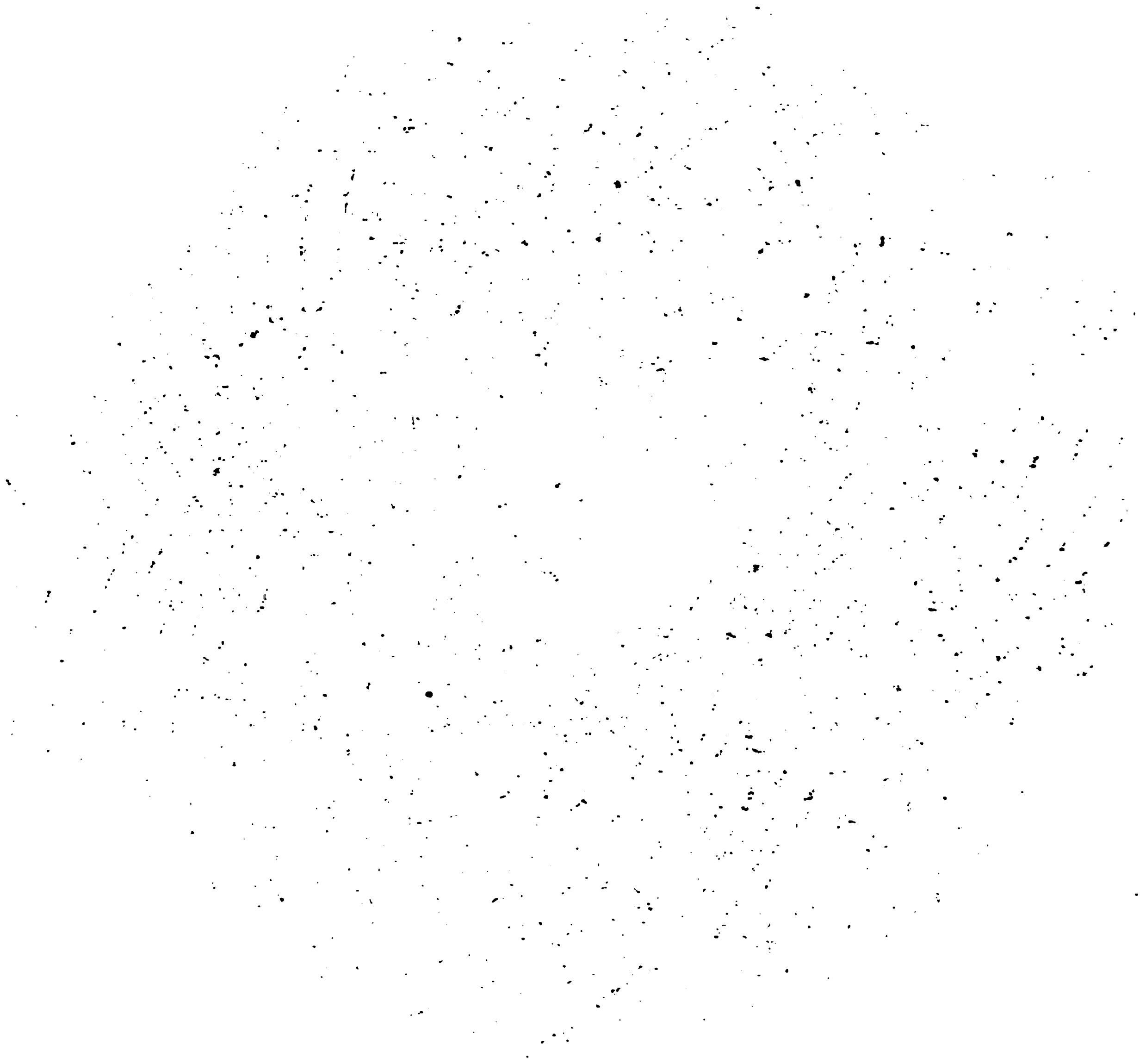


PLATE 24.

Wave Winding. Two-Circuit, Retrogressive, Four Poles, 47 Slots, 47 Commutator Bars, 47 Armature Coils, One Turn Per Coil, Two Coils Per Slot.



[illegible]

six-pole machine. In each case the coils are considered as being wound clockwise. In one instance the general progression around the armature is clockwise and in the other, counter clockwise. This results from the throw on the commutator end. The commutator contains 47 bars. Starting at bar No. 1 the progression is forward or backward, depending upon whether the end of the first coil and the beginning of the second coil is connected to bar No. 2 or No. 47. Hence the obvious names, progressive and retrogressive. At any instant there are six slots whose wires have a zero electromotive force. Therefore the commutator bars connected to these conductors will mark the approximate location of the brushes.

There is practically no difference between the progressive and the retrogressive lap winding. They produce the same electromotive force, communicate equally well, and an armature of any number of slots can be wound either way from a geometrical consideration. Other things remaining unchanged, the direction of rotation is reversed in the two cases, since the current through the armature is reversed. Possibly the retrogressive winding will require a trifle more wire.

WAVE WINDING.- A wave winding is often called a series or two-circuit winding, which as a rule it is, though not necessarily. There are usually two paths in parallel through such a winding regardless of the number of poles. The general form of the winding is shown in Plates 21, 22, 23 and 24. The heavy lines indicate the series connection of the conductors. The throw of the coils, must of course, be a fixed value. The pitch on the commutator must also be constant since the finished winding is to be perfectly symmetrical. Following the heavy line

From bar No. 1, we pass through coils A, B and C, touching the commutator at bars 17, 32 and 2. That is, with a commutator pitch of 1 and 17, the second round will start with bar No. 2, the third with bar No. 3, etc. The brushes are located as described for lap windings. In Plate 21 only two brushes are shown. Starting with the positive brush, follow through the winding clockwise. When the negative brush is reached it will be noted that one-half of all the coils on the armature have be been passed over. The same procedure counterclockwise will take the other half of the conductors. This winding is then two-circuit and the two brushes are quite sufficient, any two, one plus and one minus, will do. The addition of the other four brushes would practically amount to increasing the size of the ones shown since three brushes of like sign would be only one coil apart. If all the wire were removed from this armature and opened out the location of the brushes would be as shown in Fig. 55. When the line current becomes too large

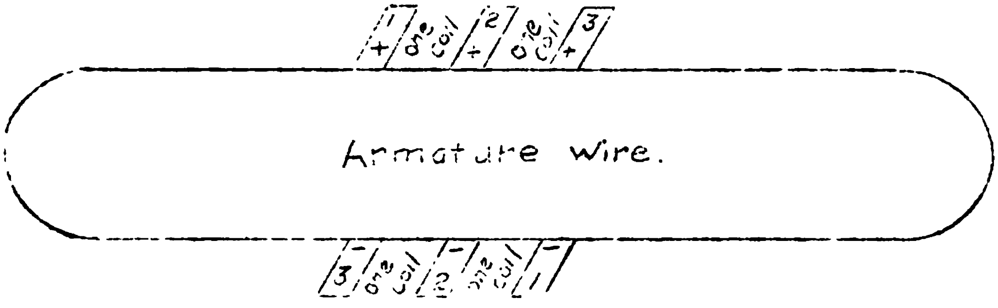


Fig. 55.

for a given size of brush, the other brushes may be added simply as an easy means of increasing the area of brush contact without increasing the length of the commutator. Plate 21 shows a progressive winding for the same reason as explained in the case of lap-wound machines. It may also be wound retrogressively, as shown in Plate 22. With a commutator pitch of 1 and 16, once

around the commutator engages bars 1, 16, 31, 46, the second round starting at 46, which is two bars back of 1. Beginning with the positive brush and following through the winding clockwise to the negative brush, only one-fourth of the winding will be passed over. The winding is therefore four-circuit or two-circuit double wound. For, beginning with the two wires leading clock-wise from bars 1 and 47, they follow around the armature in parallel and end at bars 46 and 45, respectively. The second round ends with 44 and 43, which, taken as a unit, is adjacent to 46 and 45. The brushes must be wide enough to cover two segments and thus collect current from each circuit. This is a source of considerable trouble, since it is difficult to maintain a good reliable brush contact with wide brushes covering two or more segments. For this reason this particular form of wave winding is not much used. Fig. 56 shows the arrangement, wire removed. Obviously, the total voltage generated by this winding will be one half that generated by the one shown in Plate 21 and the current capacity of the armature will be twice as great.

Whether a wave winding is made retrogressive or progressive depends upon the geometrical solution. With six poles and 47 slots the winding can only be two-circuit when wound progressively. Had there been 49 slots the winding would have been two-circuit retrogressive with the same pitch on the commutator. For all wave windings the number of slots on the armature for any given machine are made some convenient multiple of the number of poles, plus or minus one. This will give either a retrogressive or a progressive two-circuit solution for any number of poles.

Practically, all wave windings are wound two-circuit. To accomplish this the only geometrical requisite is that the first

time around the commutator the wire ends on a bar adjacent to the bar of starting, either forward or backward. The number of slots, coils per slot, and poles will very quickly determine the geometrical construction. Certain combinations require the omission of one commutator bar. Others require the omission of one coil. Sometimes a coil and a bar are both omitted and some combinations cannot be wound at all. It is interesting to note that whether a winding is lap or wave depends in no wise upon the throw of the coils, but upon the connection of the wires to the commutator.

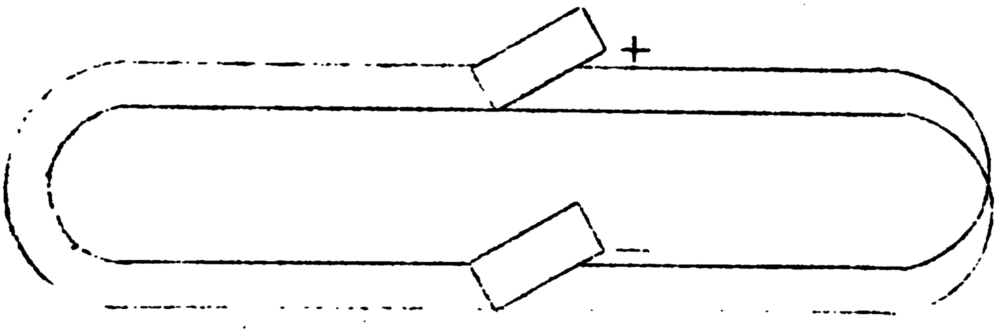


Fig. 56.

It will be noted that a change from progressive to retrogressive winding reverses the polarity of the terminals of a generator, and the direction of rotation if a motor. It sometimes happens that such an armature is to be wound with four coils per slot. This means that there will be twice as many commutator bars as there are slots, which will of course result in an even number of bars. In which case it may be necessary to omit one bar and one coil. Such omitted parts are referred to as idle. This is, however, a geometrical problem. As a rule the geometrical arrangement can best be worked out by constructing an actual diagram or arranging a table of slot numbers rather than by formulae calculations.

WINDING FORMULAE

The following formulae will assist the student in determining the pitch of the coils for the different windings.

If we let,

y = the average pitch

y_0 = the pitch of the commutator end.

y_1 = the pitch at the back end of the armature.

c = the number of conductors on the armature.

b = the number of turns per armature coil.

s = the number of armature coils.

n = the number of poles.

p = the number of pairs of poles.

m = number of windings; that is, the number of circuits in parallel and extending entirely around the armature.

Multiple Circuit, Single, Multipolar Drum.

This is the most common of all multipolar drum windings.

The pitch at one end must exceed the pitch at the other end by 2, for a single winding, M being equal to 1. each of these pitches being odd.

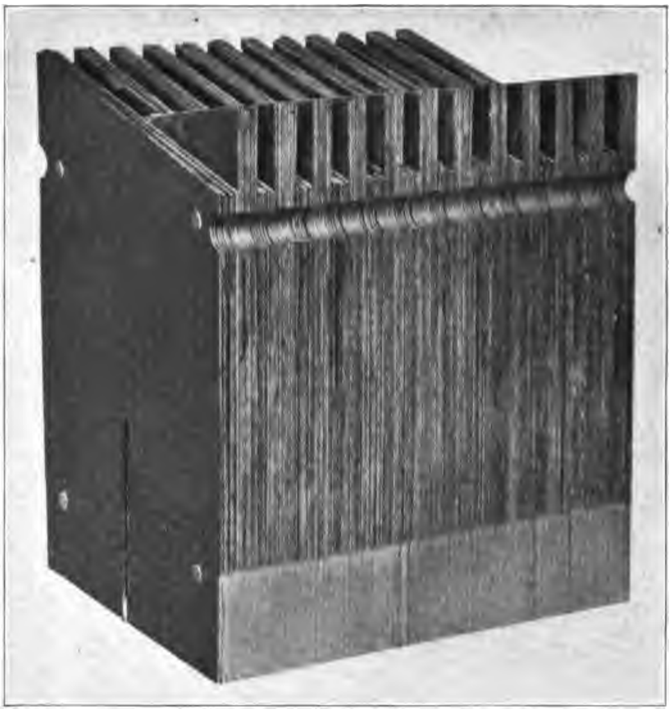
Therefore,-

$$Y_1 = Y_0 - 2$$

Multiple Circuit, Multiple Wound, Multipolar Drum Windings.

These require more than two sets of brushes and are lap windings. The number of coils must be even. y must be a little less than $\frac{2s}{n}$, Y_0 and Y_1 must be odd, and differ by 2m. therefore,

$$y_1 = y_0 - 2m \qquad (73)$$



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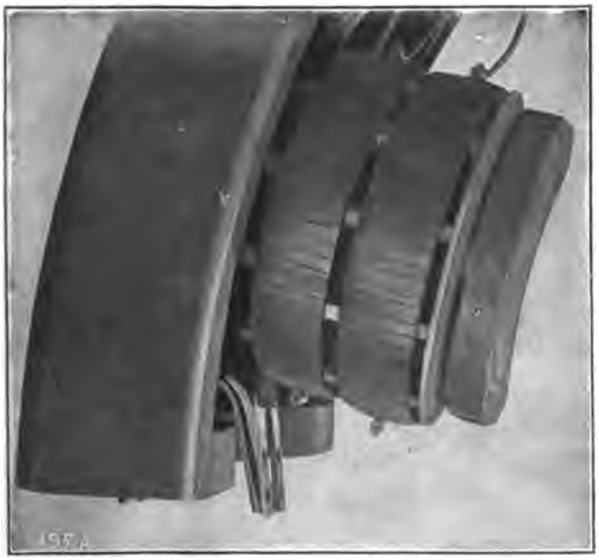
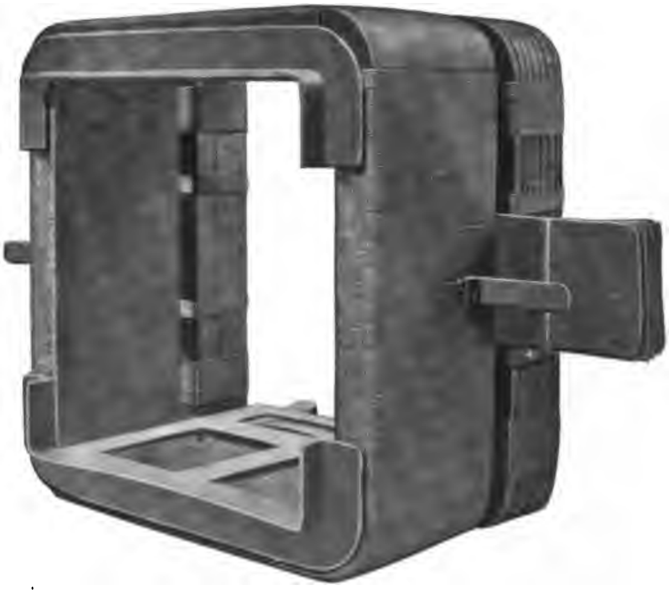
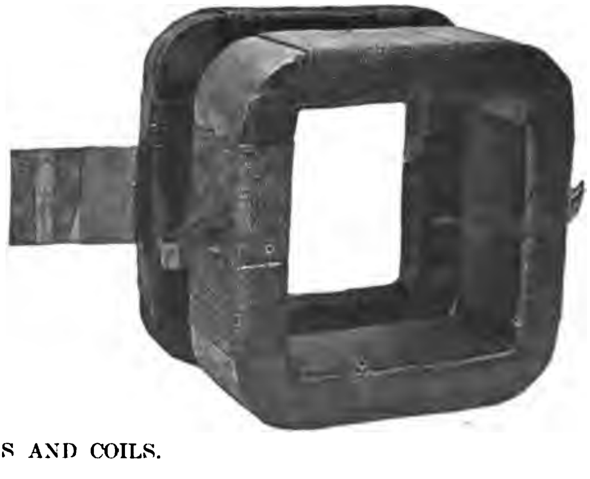


CROCKER-WHEELER.



WESTINGHOUSE.

TYPES OF POLE PIECES AND COILS.



TYPICAL FIELD POLES AND COILS.

Two Circuit, Single Wound Multipolar Drum Windings.

For this winding $2s = n \times y \pm 2$;

$$y = \frac{s \pm 1}{p} \qquad (74)$$

As a rule, $y = y_0 = y_1$, but Y_0 and y_1 may be permitted to differ by 2. y_0 and y_1 must always be odd, even when y is not an odd number.

CALCULATION OF THE FIELDS AND FIELD WINDING.

In designing the fields and field windings for direct current motors and generators, the principal points to be considered asare as follows:-

1- The type of fields to be used.

2- The proper length of the air gap.

3- The materials to be used in the different parts of the magnetic circuit, and the magnetic densities to be used therein

4- The distortion of the field in the air gap.

5- The proper shape and size of the pole faces.

6- The dimensions and the reluctance of the teeth and slot to accomplish the desired regulation and commutation.

7- The calculation of the iron losses occurring in the cor of the armature.

8- The calculation ofthe shunt and series windings.

9- Mechanical details of construction.

As has been heretofore stated, multipolar types of fields are now universally used in this country in all but small machines, so that the designer has only to decide upon the proper number of poles to be used and the percentage of the armature to be covered by the poles, in order to begin the calculations of the magnetic circuit.

The materials used in the different portions of the magnetic circuit are generally as follows: Field cores of cast steel or sheet steel, usually the latter; yoke of case iron or cast steel armature core, sheet steel.

The use of laminated pole pieces is now quite universal, owing to the consequent reduction of the eddy current losses in the pole faces. If solid poles are to be used, the teeth and slots of the armature core should be very narrow. The laminated poles may be cast into the yoke, or bolted on, present practice tending to the latter method, due to the ease with which a field coil may be removed; and the fact that it permits of a certain amount of adjustment and gives a greater uniformity of reluctance of the joint.

Cast iron, of a good grade, may sometimes be used to advantage in the yokes, especially where cast steel would need to be worked below an economical density or else be made so light as to be unstable and present a weak appearance. In cases where the yoke andpoles are to be cast of the same material, cast steel should always be used, except perhaps in very small machines, where good cast iron may advantageously be used.

Small motors, such as fan motors and those of like capacity are often made with their poles and yokes of laminated metal, the two being stamped in one piece, and then built up until the desired cross section is obtained.

The armature cores of generators and motors are always made of laminated metal, usually sheet steel having as low a hysteretic constant as is obtainable.

The magnetic densities to be used in the air gap of machines can be approximated from Table XXVI, Page 150, and the

densities to be used in armature cores below the teeth from Table XXVII, Page 150. The density in the field core is usually made to be considerably higher than that in the air gap, by making the area of the pole face somewhat greater than the area of the core.

The density to be used in the field core will depend of course upon the material of which the cores is to be made, and is generally within the limits of densities corresponding to values of H of from 15 to 50, or above the bend of the curve and approaching saturation.

ARMATURE REACTION.

Before taking up the methods of calculating the M.M.F. for the different parts of the magnetic circuit, it will be well to consider the effects which the currents in the armature have on the flux of the fields in the air gap. Suppose the machine to be running at no load, with the brushes at the neutral point of the field, that is, midway between the pole tips. We will have an approximately uniform distribution of the flux in the air gap under the poles, as indicated in Fig. 57.

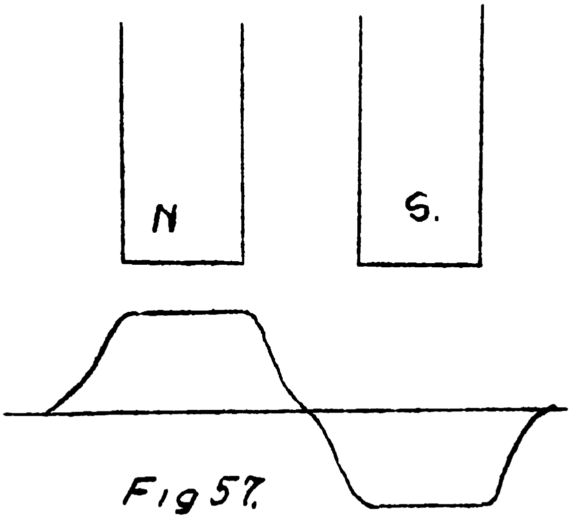


Fig 57.

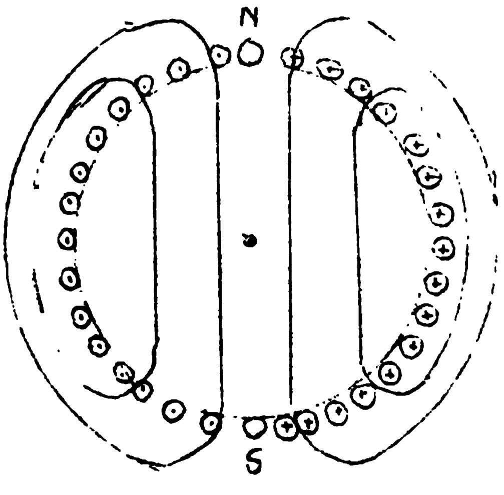


Fig 58.

Now if current be drawn from the armature, the position of the brushes remaining the same, the current in the armature conductors will magnetize the armature core, independently of the field magnets, producing poles in the plane of commutation. As shown in Fig. 58, the path of the flux produced by the armature ampere turns is such that the flux under the leading pole tip is diminished and that under the trailing pole tip is increased, so that with full load current flowing in the armature, we could get a distribution shown in Fig. 59. This effect is called the "armature cross magnetization."

But it is not possible to leave the brushes at the neutral point when current is being taken from the machine, since the requirements for commutation or reversing the current in the coil which is to be transferred from one side of the brush to the other, consists in so placing the brushes that when the coil reaches the position of short-circuit under the brush, it shall have just arrived in a magnetic field of the direction and intensity necessary to reverse the current it has just been carrying, and to build up the reversed current to a strength equal to that of the current in the circuit of which it is about to become a part. In such a case, there will be no spark when the coil passes out from the position of short-circuit under the brush. Now it is plain that, as the current delivered from the machine is increased, it will require a stronger field to reverse in the coil this stronger current. We must, then, move the brushes from the neutral point into a field of the required strength.

We now have between the tips of the poles a band of conductors carrying current, the effect of which, is to produce an M.M.F. in direct opposition to that of the field magnets, which

reduces the effective flux and the developed E.M.F. This is the armature "demagnetizing" effect, as shown in Fig. 60.

As a consequence of armature reaction and inductance, it becomes necessary to limit the value of the armature ampere turns per pole to such an amount, (at full load current) as shall not too greatly interfere with the distribution of magnitude of the magnetic flux set up by the field magnets. It is furthermore necessary to make each armature coil between adjacent segments of so low inductance as to permit of the complete reversal of the current by means of the residual flux in the commutator field.

The location and magnitude of this residual flux is determined by the number of armature ampere turns, the position of the brushes and the reluctance of the air gap, teeth and slots.

For most conditions met with in practice it is found that if the excess of field ampere turns on the air gap over the armature ampere turns does not fall below 30 % of the latter, a positive field is formed under the leading pole tip of sufficient strength to produce sparkless operation of the machines.

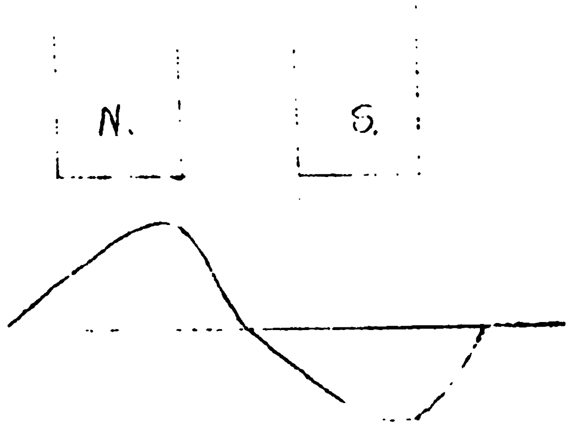
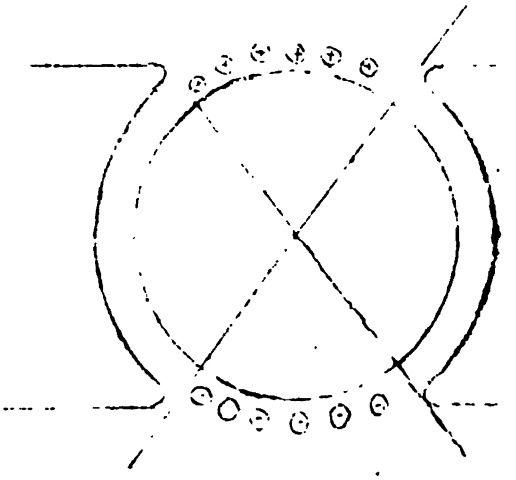


Fig. 59



Under these conditions it will be found that the armature ampere turns per pole will fall well within the limits of from 2500 to 4000 ampere turns per pole, the mean value being near 3000.

With multiple circuit windings, the armature ampere turns per pole and the volts per commutator segment may be reduced to any desired values by increasing the number of poles, or on the other hand, if we assume the limits of armature ampere turns per pole and the voltage between segments, the correct number of poles is readily determined, as well as he proper number of segments.

If we let,

E be the e.m.f. of the machine.

i_a the total current in the armature.

e_s the assumed voltage per segment.

S"I' the assumed armature ampere turns per pole.

t the number of turns between segments.

For a multiple circuit winding, we would have for the number of segments per pole,

$$N_p = \frac{E}{e_s} \qquad (75)$$

and the allowable ampere per circuit through the armature, will be,

$$I' = \frac{S''I'}{N_p \times t} \qquad (76)$$

from which the required number of circuits through the armature will be,-

$$b = \frac{I_a}{I'} \qquad (77)$$

which, for a multiple circuit winding, is equal to the number of poles.

In the case of two-circuit windings, the values of the armature ampere turns per pole andthe vltage per segment can not be adjusted by changing the number of poles, for the reason that the current divides into two paths through the armature independently of the number of poles, instead of dividing into as many paths as there are poles, as in the case of a multiple circuit winding.

However, after the required number of paths has been found by the use of equation 77, page 201, knowing that there are two paths through the armature for each winding, the number of windings required is readily determined; calling for a double, triple or quadruple winding, as the case may be. It should be borne in mind, however, that if but one set of brushes are to be used, the number of turns short-circuited by a brush no longer consists of the number of turns between adjacent segments, but includes as many coils in series as there are poles, and a high reactance voltage will consequently result in the short-circuited set.

We shall now proceed to the calculation of the armature cross magnetizing and demangnetizing effect, and the ampere turns acting upon the leading and trailing pole tips.

Where,
I' is the current flowing in each armature conductor.
S' the number of turns on the armature per pair of poles, which is equal to the number of conductors on the armature divided by 2 x the number of pairs of poles.

The number of armature ampere turns per pair of poles will then be equal to S'I'. and considering that the brushes are placed just under the leading pole tips, the demagnetizing armature ampere turns per pair of poles will be,-

$$(S'I') \times (1 - a) \qquad (78)$$

[illegible]

[illegible] of the [illegible]

[illegible] included [illegible]

[illegible] upon [illegible]

[illegible] the current [illegible]

[illegible]

Now since this demagnetizing effect is in direct opposition to the m.m.f. of the poles and increases proportionally with the armature current, it can be counteracted by the ampere turns of the series field winding. If $(Si)_f$ be the ampere turns impressed on the air gap by the shunt winding at no load, the total ampere turns to be impressed on the air gap at full load will be equal to:-

$$(Si)_f + (S'I')\,(1-a) \qquad (79)$$

Similarly, the cross magnetizing ampere turns per pair of poles will be,

$$S'\ I'\ x\ a$$

and therefore the effective ampere turns tending to produce flux under the leading pole tip will be,-

$$(Si)_{lp} = (Si)_f - a(S'I') \qquad (80)$$

and the effective ampere turns acting on the trailing pole tip will be,

$$(Si)_{tp} = (Si)_f + a(S'I')$$

which is equal to:-

$$(Si)_{lp} + 2a(S'I')$$

The distortion of the flux in the air gap may be kept within allowable limits by designing the teeth and slots so that when the no load flux is passing, the teeth will be magnetized to a point approximating saturation. The armature ampere turns will then be impressed upon a circuit, the reluctance of which will increase rapidly as the flux is incr eased; the saturation of the teeth having an effect analogous to the automatic lengthening of the air gap under the trailing pole tip, as the armature current is increased, which lessens the distortion of the field flux.

The distortion of the field may also be somewhat diminished by so shaping the pole, that the reluctance of the path of the flux due to the armature ampere turns will be great .

The length of the air gap between the tips of the teeth and the pole face is determined by mechanical conditions. Owing to the fact that it is very difficult to center the armature exactly with reference to the poles, and that the wear of the bearings tends to increase this difficulty, it is not advisable to make the air gap too small. For machines of from 1 to 10 K.W. 1/16" is a good value; from 10 to 40 K.W., 3/32 in., 40 to 100 K.W. 1/8 to 3/16 inch, and in the machines of large outputs, the air gaps vary from 1/4 to 1/2 inch, depending upon the diameter of the armature.

Having decided upon the dimensions of the poles, the armature, teeth and slots, and the length of the air gap, we may now proceed to the calculation of the ampere turns required to force the flux across the air gap, teeth and slots, and knowing the ampere turns impressed upon different parts of the air gap, determine the resulting distribution of the flux in the air gap, at full load.

If we let,

B_t be the density at the top of a tooth,

B'_t be the density at the root of a tooth

H the value of H corresponding to B_t which also represents the density in the slots at the top.

H' the value of H corresponding to B'_t

x the width of the top of a tooth,

y the width of a slot,

z equal to x + y, or the pitch of the teeth,

l_t the length of a tooth, or depth of a slot, in in.

l_a length of a single air gap in inches.

This calculation will be carried out independently of any previous assumptions relative to density in the air gap or elsewhere in the magnetic circuit, and the results obtained will then be applied to the design proper.

Begin by assuming magnetic densities in the tops of the teeth, the lower value being 4000 gausses, and succeeding values varying by 2000 gausses up to a density of 24000 gausses. It will be convenient to tabulate the assumed and calculated values, and the assumed values of B_t will constitute column 1 of this table. The values of B'_t may now be calculated and placed in column 2.

Now from the B. & H. curve of the iron of which the armature core is to be made, select the values of H and H' corresponding to the assumed values of B_t and B'_t and set these opposite the corresponding values of B_t and B'_t in columns 3 and 4. H_{av}, the average density in the slot, $\frac{H + H'}{2}$ will constitute column 5.

Now if we consider a square centimeter of the armature surface, $\frac{x}{z}$ of this square centimeter will be tooth, and the flux passing through this portion of the square centimeter will be $\frac{x}{z} B_t$; the remaining portion of the square centimeter $\frac{y}{z}$ will be slot, and the flux passing through this portion of the square centimeter will be $\frac{y}{z} H$; these two values will make columns 6 and 7, respectively. Now the sum of the fluxes passing through the two portions of this single square centimeter will give the total number of lines per square centimeter, or the average density at the surface of the armature (neglecting

space between laminae and the air ducts) which is the average air gap density. So that $\frac{x}{z} B_t + \frac{y}{z} H$ will constitute column 8.

Now since some of the space assumed to be filled with teeth is really air space, due to the insulation between laminae and the ventilating ducts, the average density will really be somewhat less than that shown by column 8. If then, we multiply the values of column 8 by the ratio of the net length of iron in the armature core to the gross length of the core, we will get the actual air gap densities, B_{ag}. These values constitute column 9.

Now the ampere turns required to drive the flux across the combined path of teeth and slots will be,

$$(Si)_{ts} = \frac{H_{av} \times l_t \times 2.54}{1.257} \qquad (82)$$

and these values may now be calculated and tabulated in column 10.

The ampere turns required to force the average air gap densities across the air gap will be,-

$$(Si)_{ag} = \frac{B_{ag} \times l_a \times 2.54}{1.257} \qquad (83)$$

the values derived from this equation constituting column 11.

If we now add corresponding values to columns 10 and 11, the sums will represent the ampere turns required to drive the different flux densities across the air gap, teeth and slots, $(Si)_t$, the values constituting column 12.

A curve should now be plotted with the values of average air gap densities, column 9, as ordinates, and the corresponding total ampere turns $(Si)_t$, column 12 as abcissae. This curve

represents then, the average density which will be obtained in the air gap for different values of effective ampere turns impressed upon the air gap, teeth and slots.

Now in equation 80, page 203 and equation 81, page 203, we have a means of calculating the effective ampere turns acting on the leading and trailing pole tips. Upon the assumption that the strength of the commutating field at full load should be just that sufficient to produce in the short-circuited coil, a current equal to that which must flow in the coil after it has passed from under the brush, which is I', the e.m.f. to be developed by the short-circuited coil due to its cutting the lines of force in the commutating field, must be equal to,

$$e_{sc} = I' \times (r_c + r_b) \qquad (84)$$

where,

r_c is the resistance of the coil.

r_b is the resistance of the path from one segment, through the brush to the adjacent segment.

The resistance of the coil is easily determined, knowing the length of the conductor and its cross section.

The resistance of brush itself is negligible in comparison with the resistance of the contact, the resistance of the latter being,

$$r_b = \frac{2 \times r'_b}{A_s}$$

where,

r'_b is the resistance per sq. inch for the current density at which the brush is operating,

A_s being that portion of a commutator segment in contact with one set of brushes.

The required edensity in the com utating field to produce h

the short-circuited coil the e.m.f. e_{sc} will then be,

$$B_c = \frac{10^8 \times e_c}{L'' \times t \times V' \times 2} \qquad (85)$$

where,

V' is the peripheral velocity of the coil in centimeters per second.

L" is the length (effective) of the armature.

The point B_c may now be located on the curve, and the corresponding abcissa may be taken as the effective ampere turns on the leading pole tip, $(Si)_{lp}$. If now we lay off from the point $(Si)_{lp}$ the value of $2a(S'I')$, we will get the abcissa corresponding to the ampere turns effective on the trailing pole tip, and the ordinate of this point will be the density under the strong pole tip. The curve between these two abcissae represents the distribution in the air gap at full load, and the average full load air gap density may be found by integrating the area between the abcissae $(Si)_{lp}$ and $(Si)_{tp}$ and finding the mean ordinate of the area, which will be the average full load air gap density.

The value so found should be made to check fairly closely with the assumed value of the no load air gap density multiplied by the ratio of the no load e.m.f. to the developed e.m.f. at full load as given by equation 65, page 155. If the difference be slight, it may be adjusted by shifting B_c up or down on the curve as may be required. If however, the discrepancy be considerable, the proportions of the teeth and slots must be altered to produce a distribution curve which will have the proper mean ordinate.

The abcissa corresponding to the mean ordinate of the area will be the required value of $(Si)_f$, the shunt ampere turns at full load. In machines designed to give constant potential at the terminals at all loads, the full load shunt ampere turns will not differ from the no load value, but in over-compounded machines, the shunt ampere turns will increase as the potential at the terminals rises.

The discussion has so far been with reference to the armature reaction of generators. In the case of a motor, the character of the reactions are analogous to those of a generator; the reactive m.m.f.s interchange their points of application as regards the leading and trailing pole tips, since in a motor the brushes are given a lag instead of a lead. The armature ampere turns tend to demagnetize the field, as in the case of a dynamo, but the cross magnetizing ampere turns produce a strong field under the leading pole tip and weaken the flux under the trailing pole tip.

If a machine be operating as a generator, it may be operated as a motor, without changing the position of the brushes, the direction of rotation being reversed.

If ϕ be the flux in the air gap under one pole at no load, the no load value of the flux in the field core will be, $\phi \times \lambda$ where λ is the coefficient of leakage, chosen in accordance with the values given in Table XXXVII, for multipolar machines.

The net area of iron in the cross-section of the field core will then be,

$$A_c = \frac{\phi \times \lambda}{B_c \times 6.45} \qquad (86)$$

where,

b_c is the assumed no load value of the density in the field core.

A_c the net area of the iron in the field core in sq. in.

If the length of the field core in a direction parallel to the shaft, be equal to the length of the armature core, which accords with the usual practice, the thickness of the core, for a solid core will be equal to $\frac{A_c}{L}$, but if the core is of laminated iron, the thickness must be increased in the ratio of the gross to the net length of iron, the thickness becoming in this case,

$$\frac{A_c}{L \times f} \qquad (87)$$

The cross section of the yoke, for a multipolar machine will be,

$$A_y = \frac{\phi \times}{2 \times B_y \times 6.45} \qquad (88)$$

where,

B_y is the assumed no load value of the density in the yoke.

TABLE XXXVII.

LEAKAGE COEFFICIENTS FOR MULTIPOLAR FIELDS.

Capacity in K.W.	Leakage Coefficient.
1	1.35
2	1.25
5	1.20
7	1.18
10	1.16
25	1.15
50	1.14
100	1.12
200	1.11
300	1.10
500	1.09
1000	1.08

The cross section of the armature core below the teeth will be,

$$A_{ac} = \frac{\phi}{2 \times B'' \times 6.45} \qquad (89)$$

where,

A_{ac} is the net area of iron in the cross section below the teeth.

B'' is the assumed no load value of the density in the core below the teeth.

The depth of the iron below the teeth will then be,

$$d_c = \frac{A_{ac}}{L \times f} \qquad (90)$$

where,

L is the gross length of the armature core in inches.

f is the percentage of the length which is iron.

No rule can be laid down for the determination of the length of the poles radially. Usually a length equal to about 1.25 to 1.75 times the width perpendicular to the shaft will give a good proportion. Sometimes it is necessary to make the pole longer, in order to accommodate the shunt field and series coil; often it can be made shorter than indicated above. Generally speaking, thepoles should not be made longer than necessary, for this unnecessarily increases the outer diameter of the yoke and the size and weight of the machine.

Having determined the general dimensions of the machine, a drawing of a portion of the magnetic circuit, as shown in Fig. 59, should be made to scale. From this the length of the magnetic circuits to the different parts are readily determined, by measuring the mea paths. Since each complete path of the flux is surrounded by two field coils, it is only necessary

for one coil to supply the m.m.f. necessary to drive the flux from the center of the yoke between poles to the mid point of the armature core corresponding.

From the lengths of the paths in centimeters, and the values of H, corresponding to the densities in the different parts, the ampere turns to be provided by the shunt coils may be calculated.

The ampere turns required by the air gap, teeth and slots at no load, may be taken from the curve already plotted, this being the abcissa corresponding to the no load air gap density.

The size of wire to be used in the shunt field winding may be calculated by the use of a modified form of equation 20, page 75.

$$(m) = \frac{(K) \times L' \times n \times (Si)_f}{12 \times (E'_o - E_r)} \qquad (91)$$

where,

n is the number of coils to be placed in series.

E'_o is the potential between the points to which the terminals of the shunt winding are to be connected.

E_r is the drop in volts due to the field rheostat, which is usually from 15% to 20 % of E'.

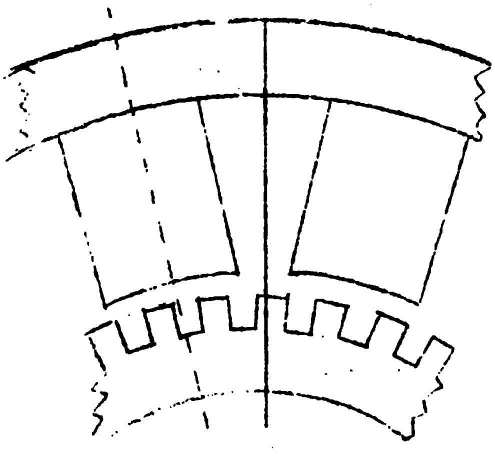


Fig. 61

The temperature of the field winding should not exceed 60° C. for continuous operation at full load. For economy in copper it is advisable to operate at a temperature somewhat near this value.

Allowing then a temperature rise of 40° C. above the air, we have, as a modification of equation 21, page 78, for the value of the current,

$$I_s = \frac{S \times 40}{83 \times E_c} \qquad (92)$$

where, S is the external area of the coil exposed to the air.

E_c is the potential measured around the terminals of one coil.

The radiation of the coil will be increased by leaving a space of about 1/8 inch between it and the pole, which admits of a circulation of air between the winding and the pole. Some radiation will also take place from the ends of the coil, so that in calculating the radiating area, it may well be assumed that one square inch of the ends is equal in radiating value to about 1/2 that area on the cylindrical surface.

It will be found that usually the current density in the field winding will fall within the limits of from 800 to 1200 (m) per ampere. The calculations should be carried through until the required area checks with that assumed for the winding space, just as in the case of an electromagnet. If the winding comes out too deep, and the radiating area too small, it will be necessary to lengthen the pole and the coil. In assuming the length of the coil for the shunt winding, a sufficient space should be left to provide for the series winding, which is usually placed at the end of the pole nearest the armature. In small machines, the shunt and series winding may be supported on the same spool. In machines of very large output, the series coil is sometimes mounted independently of the shunt coil, in order to secure more radiating area.

The voltage to be developed at full load may be calculated now, and the series ampere turns necessary determined.

The e.m.f. to be developed at full load will be,-

$$E = E' + I_a (R_a + R_b + R_s) \qquad (93)$$

Where,

E' is the full load e.m.f. at the terminals.

R_a, R_b and R_s being the resistances of the armature winding respectively. The resistance of the series winding being assumed according to the directions given on page 152; it will usually be from .5 to .75 of the value of R_a.

As stated on page 155, the increase of potential necessary to overcome the various drops at full load is obtained by slightly increasing the flux in the air gap as the load comes on the machine. The density in each portion of the magnetic circuit will at full load be increased to a value equal to the no load density multiplied by the ratio $\frac{E}{E_0}$. From the values of H, corresponding to the full load densities, the ampere turns for each part of the circuit may be calculated. To these must be added the back ampere turns of the armature, so that the full load value of all the shunt and series ampere turns must be,

$$(Si)_{f+s} = \frac{\Sigma Hl}{1.257} + (Si)_t + (S'I')(1 - a) \qquad (94)$$

Where,

ΣHl is the value of the gilberts for the pole piece, the yoke and the armature core below the teeth.

$(Si)_t$ the full load value of the ampere turns to be impressed upon the teeth and slots, which is the abcissa of the mean ordinate of the area on the curve

$(1 - a)(S'I')$ the demagnetizing ampere turns of the armature.

Now if we subtract from the total ampere turns at full load the ampere turns due to the shunt winding, the remainder must be

supplied by the series winding, so that the series ampere turns will be,

$$(Si)_s = (Si)_{f+s} - (Si)_f \tag{95}$$

and the number of series turns will be,

$$S' = \frac{(Si)_s}{I} \tag{96}$$

As explained on page 209, for a machine developing constant potential at the terminals, the shunt ampere turns at no load and at full load will have the same value, but on over-compounded generators, the shunt ampere turns at full load will be equal to the no load value, multiplied by the ratio of the full load e.m.f. between the armature terminals (for a short shunt connection) to the no load e.m.f. between the same points. Therefore the full load value will be,

$$(Si)_f = (Si)_{f_o} \times \frac{E + (R_s \times I)}{E_o} \tag{97}$$

The number of series turns placed on a pole should not be made a whole number, but should be the nearest whole number given by equation 96 + or - 1/2 a turn, so that the ends of a coil will come on opposite sides of a coil and facilitate connection between adjacent coils. If using such a number will not give the required value of $(Si)_s$, then the series coils, as a whole, should be shunted by a resistance of such a value that the proper current will flow through the series winding to give the required ampere turns. The series conductor in small machines may be of round wires, but in machines of larger sizes, it should be rectangular in cross section, usually wound in a single layer, with the strips on edge. The cross section should be such that the temperature will not rise above the allowable

value, and the drop be within the limits which have already been specified.

The percentage which the shunt field current will be of the total armature current varies with the output of the machine.

CALCULATION OF CORE LOSSES.

In determining the core loss which will take place in a machine yet to be built, it is necessary to resort to the use of emprical formulae. Several methods of calculating the iron loss which will occur in a mass of iron in which the flux is uniformly distributed, and the constants of the metal are known exist, but since in the core of the armature of a dynamo, the flux is not uniformly distributed, and the distribution changes with a change in the load, these formulae will not apply. Further the eddy current losses occurring in the faces of the pole and in the core of the armature, are very difficult of calculation, since these are affected by the machine work on the iron, the degree of insulation provided between the laminae and the pressure with which the sheets are held together. This being the case, it is evident at once that a means of calculation based upon experimental results from machines already built will result in greater accuracy.

We know that the iron losses will depend largely upon the density at which the iron is to be worked and the rate of the reversals of the flux in the metal, so that an experimental constant which may be multiplied by the factors, frequency and flux density to give the watts loss which will occur in a unit mass of the metal, will be the best and most desirable form for the empirical equation.

In Fig. 17, page 19 are three curves giving the core loss in watts per pound of armature iron as abcissae and density in the core below the teeth multiplied by the number of cycles per second, as ordinates.

To get the core loss for a given machine, multiply the density in kilo-gausses below the teeth by the number of cycles per second, with this value as an ordinate, find the corresponding abcissa, which will be the watts per pound of armature iron, including the teeth.

$$\text{The number of cycles} = \frac{\text{rev. per min. x pairs of poles}}{60}$$

ARMATURE TEMPERATURE RISE AND VENTILATION.

As heretofore stated, the temperature rise of an armature depends upon the amount of energy dissipated in its core and conductors in the form of heat, upon the extent of the armature surface from which radiation takes place and upon the mean peripheral velocity of this area.

In modern machines the radiating area is made large by the adoption of the multipolar type of armature, which is short and of large diameter. Ventilating ducts are also placed in the laminated cores by placing multi-fingered light brass distance pieces between sections of the core; these admit of a free passage of air up between the discs so separated, and across the conductors where they span the gaps made by the ducts.

The width of the ventilating ducts is usually made equal to the circumferential width of an armature tooth, or may be made from 1/4 to 1/2 inch in width The number used depends upon the radiating area necessary and the size of the armature; it varies from one to 10, from two to four being generally found in

moderate sized machines.

The radiating power of an armature is gauged by its radiation coefficient, K', which may be defined as the ratio of the total armature heat radiation expressed in watts, to the product of the area of the armature surface (s) which revolves under the pole faces, in square inches, and the temperature (T) of the armature core in degrees centigrade, above the air. The radiating power of an armature is really dependent upon the actual radiation of heat from the entire exposed surface of the armature core and windings, but it is referred to the circumferential air gap surface in that this furnishes a means of comparison of the radiating power of all armatures.

As a result of a very elaborate series of tests made at Cornell University, the following conclusions were drawn. (See Timmerman 's results, p. 349, Trans.A.I.E.E. Vol. 10, 1893.)

1. That an increase in the temperature of a surface causes an increased radiation of heat per degree rise in temperature, but that the rate of increase diminishes as the temperature increases, and an increase in the amount of heat generated increases the temperature of the surface, but less proportionally.

2. That the effect of the pole faces above a surface is to interfere with the radiation of heat. As the proportion of the surface covered by the poles is increased, the amount of heat radiated per degree rise of temperature becomes less.

3. As the peripheral velocity of a surface is increased, the amount of heat liberated per degree rise in temperature is increased, but the rate of increase becomes less as the peripheral velocity is increased.

Embodying the principles just set forth, Table XXXVIII gives the radiation coefficients for moving surfaces. The values give the number of watts radiated per square inch per degree rise (Centigrade) in the temperature of a surface above that of the air for various velocities and percentages of polar

TABLE XXXVIII.

RADIATION COEFFICIENTS.

Peripheral velocity in ft. per minute.	Watts radiated per degree C. rise in temperature.			
Value of "a"	.8	.7	.6	.5
0	.00909	.01000	.01053	.01111
600	.01250	.01351	.01429	.01493
1200	.01563	.01639	.01786	.01786
1800	.01818	.01887	.01961	.02010
2400	.02000	.02062	.02128	.02174
3000	.02083	.02128	.02174	.02222
4500	.02128	.02174	.02222	.02273
6000	.02174	.02222	.02273	.02327
9000	.02222	.02273	.02327	.02381
Value of "a"	.4	.3	.2	.0
0	.01152	.01205	.01250	.02259
600	.01563	.01613	.01667	.01717
1200	.01852	.01923	.02000	.02077
1800	.02083	.02151	.02222	.02270
2400	.02222	.02263	.02325	.02381
3000	.02273	.02327	.02381	.02439
4500	.02327	.02381	.02439	.02489
6000	.02381	.02439	.02489	.02530
9000	.02439	.02489	.02530	.02530

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embrace.

If, therefore,

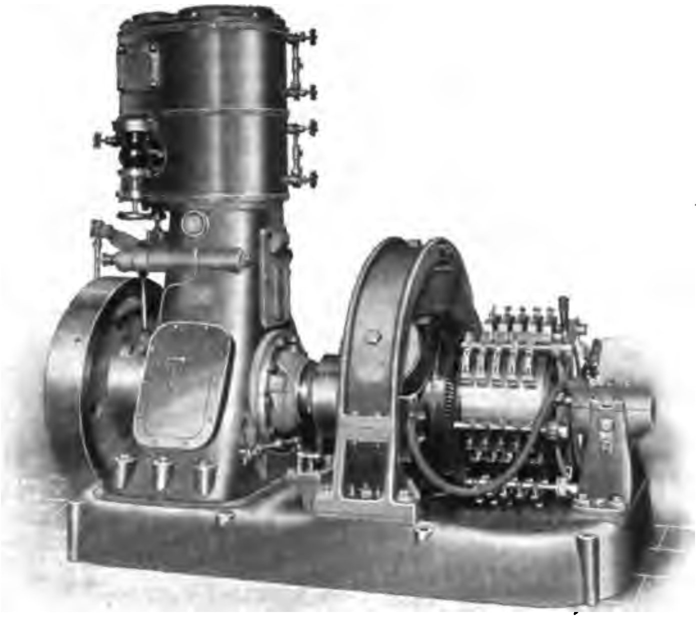
S be the external cylindrical surface of the armature which passes under the poles, in square inches.

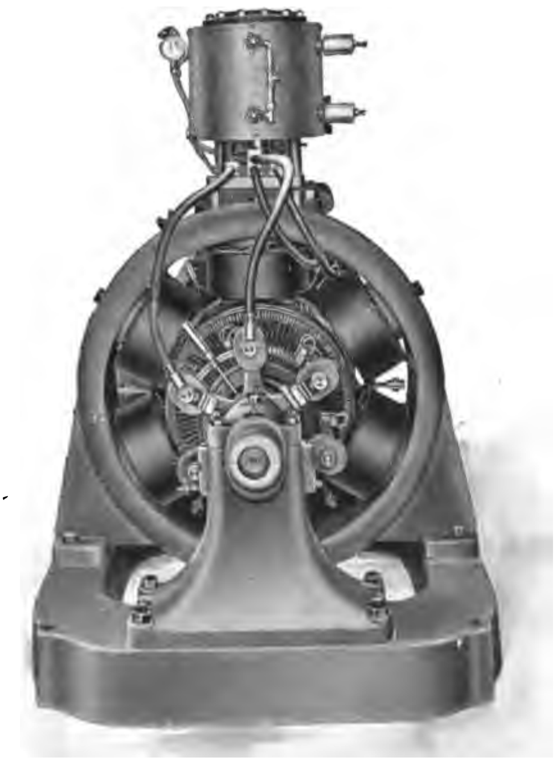
S_1 be the external cylindrical surface of the armature which does not pass under the poles, in square in.

S_2 be the internal cylindrical surface of the armature core in square inches.

S_3 the radiating surface of the core and conductors at the two ends of the armature in square inches.

S_4 the radiating surface presented by the two sides of a ventilating duct, in square inches.





SMALL ENGINE TYPE UNITS OF GENERAL ELECTRIC CO.

K, K_1, K_2, K_3, K_4, the radiation coefficients of these several surfaces, corresponding to their average peripheral velocities and percentages covered by the poles.

N the number of ventilating ducts.

$$K' = \frac{SK + S_1K_1 + S_2K_2 + S_3K_3 + S_4K_4}{S} \qquad (98)$$

Where,

K' is the radiation coefficient of the armature, as defined on page 218.

The temperature rise of the armature under continuous operation at any given load may now be calculated by a modification of equation 76, page 153.

$$T = \frac{W_c + I_a^2R_a}{K' \times S} \qquad (99)$$

Where,

T is the temperature rise of the armature in degrees Centigrade above the air, as would be indicated by a thermometer.

W_c the core loss in watts.

The constants in Table XXXVIII having been determined by measuring the temperature of the armature surface by means of a thermometer, we would expect equation 99 to give similar results.

The temperature measured by resistance method, generally equals about 1.25 that by the thermometer, owing to the fact that the inner parts of the core are at a higher temperature than the external surface, so that in order to get the actual temperature of the inner windings, the results of equation 99 should be multiplied by 1.25 and added to the temperature of the air.

The temperature of the machine should be calculated for no load, full load and at 25 % and 50 % overload.

CALCULATION OF EFFICIENCY.

Knowing now the output of the machine and all the internal losses, with the exception of the bearing friction and windage, which may be assumed as follows: For machines belt driven, at speeds of from 1500 to 350, the capacities ranging from 50 to 500, these losses should range from 3 % of the output for the smaller sizes to 1 % in the larger machines. In genera direct connected machines have lower losses owing to low speed and good alignment, usually from .5 %, to .35 %, depending upo the output and speed.

The commercial efficiency of a machine will then be,

$$\frac{W}{W + W_a + W_c + W_s + W_S + W_b + W_f} \qquad (100)$$

where,

W is the output into the external circuit at the load, considered equal to the terminal e.m.f. x external current.

W_a the I^2R loss in the armature winding.

W_c the core loss of the armature and pole tips.

W_s the watts loss in the shunt winding and rheostat.

W_S the watts loss in the series winding.

W_b the watts loss due to resistance of brush contact resistance.

W_f the brush and bearing friction losses and windage.

W_s W_c and W_f may be assumed to be the same for all loads, the other losses varying with the current output.

The efficiency should be calculated for a number of different loads, and a curve of efficiency as ordinates and watts output as abcissae, should be plotted.

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Design No. 8.

It is required to design a 10.5 K.W., high speed, belted, D.C. generator, to give a constant potential of 160 volts at its terminals, the temperature rise for continuous operation at full load not to exceed 40° C. above the air.

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This e.m.f. has been chosen so that the winding may be tapped and connected to collector rings, to have a difference of potential of 110 volts, A.C. between them.

By reference to Table XXIV, page 146, we find that the number of poles for a machine of this output would be 4.

In order that we may have a standard frequency of the A.C. current, we will assume a speed of 1800 r.p.m., which will give 60 cycles per second. This speed is still somewhat below the upper limit for a machine of the capacity as given in Table XXI, page 143.

By reference to Table XXV, page 147, we find the peripheral velocity for a machine of this type and output to be from 3500 to 5500 feet per minute; we will assume 4400 f.p.m. for the armature surface, so that the outside diameter of the armature core will be,-

$$d = \frac{4400 \times 12}{1800 \times} = 9.25 \text{ inches, which}$$

comes well within the limits given by Table XXX, page 146.

Assuming a ratio of length of armature to diameter, in accordance with Table XXX, page 157, of .72, we will have as the cross length of the armature core, 9.25 x .72 = 6.66, say 6-5/8 inches.

In accordance with the values given on page 204, we will

assume a length of air gap of 3/32 inches = .09375 in., so that the bore of the poles will be 9.25 + 2(.09375) = 9.4375 = 9-7/16"

Assuming 70 % of the armature surface to be covered by the poles, the circumferential width of a pole will then be,

$$\frac{.7 \times 9.4375 \times \pi}{4} = 5.28, \text{ say } 5\text{-}1/4 \text{ inches, which}$$

gives a pole face 5-1/4 x 6-5/8 in, assuming a length of the pole to be equal to the length of the core, which is a very good proportion. The area of a pole face will then be,

$$5.25 \times 6.625 = 34.78 \text{ sq. in.} = 224.25 \text{ sq. cm.}$$

We have assumed a speed and peripheral velocity near the upper limits, so we will assume an air gap density near the lower limit, say 4,150 gausses, so that our machine will still have reasonable proportions. By equation 59, page 153, we have $\phi = B \times A$, so that the flux per pole at no load will be,

$$\phi = 4150 \times 224.25 = 930,000 \text{ maxwells,}$$

and from equation 58, page 152, the required number of conductors will be, assuming that we will use a four circuit winding,

$$C = \frac{160 \times 10^8}{930,000 \times 30} = 574 \text{ conductors.}$$

A better number would be 578, since it is divisible by 4, the number of poles, so we will use 578 conductors and reduce the no load air gap density in the proportion,

$$\frac{4150 \times 574}{578} = 4,130 \text{ gausses.}$$

By reference to Table XXXII, page 158, we find 45 to be the average number of slots for an armature of this diameter; we will use 48 slots, which will give $\frac{576}{48}$ = 12 conductors per slot.

On page 161, we note that these should be from 50 to 60 segments per pair of poles, so that we should have about 90 segments

in our commutator. By making the number of coils equal to twice the number of slots, winding and insulating two coils together as one, we will then have 96 coils, 96 segments, and 6 conductors of 3 turns per coil. This will give an average voltage between segments of $\frac{160}{24} = 6.66$ volts, which is permissible.

We will now find the required dimensions of our armature conductors, and see whether they can be placed in the space available.

We will assume a shunt current of 5 %, so that at full load the total armature current will be,

$$I_a = \frac{10.5 \times 1000 \times 1.05}{160} = 69 \text{ amperes,}$$

and using a single, four circuit winding, the current in one path through the armature will be,-

$$I' = \frac{69}{4} = 17.25 \text{ amperes.}$$

Assuming 600 (m) per ampere, we have for the cross section of an armature conductor,-

$$(m) = 17.25 \times 600 = 10{,}365 \ (m),$$

which is almost equivalent to a # 10 B. & S. wire which has 10,381 (m), so we will use the #10 wire.

The circumference of an armature 9.25 inches in diameter will be $9.25 \times \pi = 29.06$ inches, and using 48 slots, the pitch of the teeth will be,-

$$\frac{29.06}{48} = .6054 \text{ inches.}$$

From Table I, page 47, the diameter of # 10 wire, d.c.c. is .117 inches. We will get a good proportion of slot by winding 2 wires side by side and 6 deep, so that the uninsulated

coil (double) will measure (2 x .117) x (3 x .117) or .254 x 351 inches.

If we make the slot 5/16 = 3125 in. wide, this will allow for insulation on either side, between the coil and the core,

$$\frac{.3125 - .254}{2} = .02925,$$ which is sufficient for a machine of this output and e.m.f.

The width of a tooth at the top will be,

.6054 - .3125 = .2829 inches, which gives a ratio of slot to tooth of $\frac{.3125}{.2829} = 1.104$, which corresponds with the mean ratio given on page 160.

In page 160 we find the average ratio of depth to width of slot to be about 3, so that the depth of the slots should be,

3 x .3125 = .9375 inches.

Two double coils will take up:

(6 x .117) + (4 x .02925) = .819 inches. This will leave .9375 - .819 = .1185 in. for the retaining wedge.

The average pitch for a single, multiple circuit winding is $\frac{2s}{n}$ which for our armature would be equal to $\frac{2 \times 96}{4} = 48$, and the back pitch would then be 47 and the front pitch 49, Since four coils will appear in one slot, a back pitch of 47 will carry us from the bottom of one slot to the top of the twelvth one, so that the width of a coil will be approximately 11 times the pitch of the teeth, this being the distance from the center of one slot to that of the twelvth one from it.

Laying the coil off on the drawing board according to the directions given on page 151, we find the length of one turn to be 34 inches, and allowing 3 inches for each connection to the commutator, the length of conductor in one coil will be,

$$\frac{34 \times 3 + (2 \times 3)}{12} = 9 \text{ feet.}$$

The total length of conductor on the armature will then be,

$$9 \times 96 = 864 \text{ feet.}$$

The resistance of all the wire on the armature in series will be, at 60° C,

$$\frac{864 \times 12.02}{10381} = 1.02 \text{ ohms.}$$

The resistance of one of the four paths will then be, not deducting the coils short circuited by the brushes,

$$R_a' = \frac{1.002}{4} = .2505 \text{ ohms;}$$ and the resistance of four of these paths in parallel would be, by equation 73, page 152,

$$R_a = \frac{.2505}{4} = .06262 \text{ ohms.}$$

The I^2R loss in the armature would then be at full load, according to equation 74, page 152,

$$69 \times 69 \times .06262 = 298 \text{ watts.}$$

Assuming that a brush will cover four segments, short circuiting three coils, the number of active coils at any instant will be,

$$96 - (4 \times 3) = 84,$$ and the resistance of the active coils in one path will be,

$$\frac{9 \times 21 \times 12.02}{10,381} = .2195 \text{ ohms,}$$ and the armature drop at full load will be,

$$.2195 \times 17.25 = 3.78 \text{ volts.}$$

In calculating the loss in watts due to armature resistanc all the winding should be considered, as there is a loss in the short circuited, as well as the active coils. The short cir-

circuited coils do not, however, offer any resistance in the active portion of the armature, so that in calculating the armature drop, only the active portion of the winding should be considered.

It will now be well to carry the design of the armature to a point where the core loss and temperature rise may be calculated.

We find on page 220 that two ventilating ducts, each 1/4 inch wide should be used; allowing 10 % for the space between laminae, the gross length of the core being 6.625 inches, the net length of iron will be,

$$(6.625 - .5)\ .9 = 5.51 \text{ inches.}$$

Assuming a magnetic density of 9,500 gausses in the core below the teeth, the cross section of the core below the teeth must be,

$$A_c = \frac{224.25 \times 4,130}{2 \times 9,500 \times 6.45} = 7.55 \text{ sq. in.}$$

and the depth of the core below the teeth must then be,

$$\text{depth} = \frac{7.55}{5.51} = 1.37, \text{ say } 1\text{-}3/8 \text{ inches.}$$

If there were no slots, the volume of the core would be,

$$\frac{9.25 + 4.625}{2} (\pi \times 5.51 \times 2.3125) = 277 \text{ cu.in.}$$

The volume of the slots is,

$$48 \times .9375 \times .3125 \times 5.51 = 77.5 \text{ cu. in., so}$$

that the weight of the core will be,

$$w = (277 - 77.5) \times .277 = 55.3 \text{ lbs.}$$

The cycles x kilo-gausses = 60 x 9.5 = 570, and from an extension of the curve in Fig. 17 page 19, we find the watts loss per pound of core to be 7.5, so that the core loss in watts will be 55.3 x 7.5 = 415 watts, due to the high frequency used.

In accordance with page 220, the surface of the armature which passes under the poles is,

$$S = 9.25 \times \pi \times 6.625 = 193 \text{ sq. in.,}$$ and from the table on page 219, K for this surface = .02174; so that KS is equal to 193 x .02174 = 4.2

The coils extend 3.81 inches beyond the core at each end of the armature, so that,

$$S_1 = 9.25 \times \pi \times 3.81 \times 2 = 222 \text{ sq. in.,}$$ and K_1 is equal to .02489, so that $S_1K_1 = 222 \times .02489 = 5.53.$

The inner area of the core will be,

$$S_2 = 4.625 \times \pi \times 6.625 = 96.2 \text{ sq. in.,}$$ for which the peripheral velocity will be,

$$\frac{4.625 \times \pi \times 1800}{12} = 2{,}180 \text{ feet per minute,}$$ so that

$K_2 = .0235$, so that $K_2S_2 = .0235 \times 96.2 = 2.26$

The two ducts being equal to two ends, the ends and the ducts may be considered together, so that S_3 will be,

$$\frac{9.25 + 4.625}{2} \times 4 \times \pi \times 2.3125 = 202 \text{ sq. in.,}$$ for which the peripheral velocity will be,

$$\frac{9.25 + 4.625}{2} \times \frac{1800}{12} \times \pi = 3275 \text{ feet per min.}$$

so that $K_3 = .0245$; then $K_3S_3 = .0245 \times 202 = 4.95$

Then by equation 98, page 220, we have for the radiation coefficient,

$$K' = \frac{4.2 + 5.53 + 2.26 + 4.95}{103} = .0897$$

Then by equation 99, the rise in temperature due to core loss alone will be,

$$T' = \frac{415}{.0879 \times 193} = 24.5^\circ \text{ C above the air.}$$

And the rise at full load will be,

$$T'' = \frac{298 + 415}{.0879 \times 193} = 42.0^\circ \text{ C. above the air,}$$

which checks sufficiently close with the specified value of 40° C.

Had it been found that the temperature rise did not come up to near the specified value, it would have been advisable to increase the current density in the copper of the armature. Had the temperature come up too high, it would have been necessary to increase the cross section of the conductors and increase the radiating surface of the armature.

By equation 77, page 154, the maximum current which the machine would stand with an overload temperature rise of 65° C. is:

$$I_m = \frac{.0879 \times 193}{.0626} \left(65 - 24.5 \right) = 105 \text{ Amp.}$$

In accordance with page 161, assuming a commutator peripheral velocity of 2800 feet per minute, we have for the diameter of the commutator,

$$d = \frac{2800 \times 12}{1800 \times \pi} = 5.95, \text{ say 6 inches,}$$

and the circumference of the commutator will then be $8 \times \pi =$ 18.86 in.

Allowing .025 for the insulation between segments, in accordance with Table XXXV, page 164, since there are 96 segments, we have as the thickness of a segment,

$$t = \frac{18.86 - (96 \times .025)}{96} = .172 \text{ inches.}$$

Assuming that a brush should cover between 3 and 4 segments so that three coils will always be short circuited, the thickness of a brush must be,

(4 x .172) + (3 x .025) = .76 inches; so that if we make the thickness of the brush 5/8 inches, the arc of the circle of which 5/8 inches is the chord, will have a sufficient width to keep three coils short circuited.

Assuming a current density of 25 amperes per square inch of brush contact, the area of one set must be $\frac{17.25 \times 2}{25} = 1.38$, the thickness being .625 inches, the width of the set must be $\frac{1.38}{.625} = 2.208$ inches. This can well be divided up between three brushes, the width of each being $\frac{2.208}{3} = .735$, say 3/4 inches. So that making the brush 3/4 x 5/8", the area of one set will be 3 x .625 x .75 = 1.414 sq. in.

The length of the commutator must then be,-

(3 x .75) + (2 x .25) + (2 x .25) = 3.75 inches.

Assuming a pressure of 1.2 lbs. per sq. inch, the resistance of double contact will be .075 ohms. Then by equation 59, page 171, the resistance of one positive and negative contact will be,

$$R_b' = \frac{.075}{1.414} = .053 \text{ ohms; and by equation 60,}$$

page 172, the drop due to brush contact will be,-

17.25 x 2 x .053 = 1.829 volts.

By equation 61, page 172, the resistance between brush terminals and commutator surface will be,

$$R_b = \frac{2 \times .053}{4} = .0265 \text{ ohms.}$$

The watts loss due to resistance of brush contact will be,

69 x 69 x .0265 = 126.15 watts.

Using a coefficient of friction of .3, the watts loss due to brush friction will be,

$$\frac{1.2 \times 1.414 \times \pi \times 6 \times .3 \times 746 \times 1800}{12 \times 33,000} = 130 \text{ watts.}$$

The cylindrical surface of the commutator from which radiation will take place is $S_1 = 6 \times \pi \times 3.75 = 71$ square inches, and the value of $K_1 = .024$ so that $K_1S_1 = 1.7$

The area of two ends, since the commutator will be solid will be $2 \times \pi \times 3^2 = 56.8$ square inches.

The peripheral velocity of the surface will be 1400 feet per minute, so that K_2 will be .021, so that $S_2K_2 = 56.8 \times .021 = 1.195$.

The area of the brushes and parts of the brush holders from which radiation will take place is,

for the brushes, $12 \left[(2 \times .625 \times 2) + (2 \times .75 \times 2) + (.75 \times .625)\right]$ which is equal to 71.6 square inches

For the brush holders, $12 \left[(1.25 \times .875 \times 2) + (1.25 \times 1 \times 2)\right]$ which is equal to 56.3 square inches. The sum of those two is

$$S_3 = 71.6 + 56.3 = 127.9 \text{ sq. in.}$$

The value of K_3 is .01295, so that $K_3S_3 = .01295 \times 127.9 = 1.65$

The value of KS for the entire commutator will then be,

$$KS = 1.7 + 1.195 + 1.65 = 4.545,$$

so that the temperature rise of the commutator will be by equation 63, page 172,

$$T = \frac{126.15 + 130}{4.545} = 56.6^\circ \text{ C, which is}$$

within the limit of 60° C. as given on page 172.

Having determined the dimensions of the commutator and brushes we can calculate the reactance voltage of the coil during commutation.

By equation 64, page 174, the flux which would be set up by one ampere flowing in one coil would be,

$\phi_c' = 3 \times 5.51 \times 20 = 330.6$, but since there are three coils short circuited by one brush, and further because one half of the flux set up by the coils short circuited by each of the adjacent brushes is linked with the coil under consideration, to get the total flux which would be linked by the turns of the coil, we must multiply ϕ_c' by 3 for the three coils, and by 2 for the two halves of the coil under adjacent brushes, so that the flux for unit current will be,

$$\phi_c = 3 \times 5.51 \times 20 \times 3 \times 2 = 1980 \text{ maxwells.}$$

The inductance of one coil of three turns is then, by equation 66, page 174,

$$\frac{1980 \times 3}{10^8} = .0000594 \text{ henrys.}$$

By equation 68, page 175, the frequency is,

$$\frac{1800 \times \pi \times 6}{2 \times .625 \times 60} = 452.5 \text{ cycles per second.}$$

The reactance is then, by equation 69, page 175,

$.0000594 \times 2 \times \pi \times 452.5 = .1686$ ohms, and the reactance voltage will be, by equation 70, page 175,

$.1686 \times 17.25 = 2.94$ volts. The average voltage per commutator segment is $\frac{160 \times 4}{84} = 7.6$ volts, so that the value of the reactance voltage is within allowable limits.

By equation 71, page 177, we find the diameter of the shaft within the core to be,-

$$d_c = 1.2 \times \sqrt[4]{\frac{10500}{1800}} = 1.86'', \text{ say } 1\text{-}7/8''$$

The winding which we have adopted for this machine is a multiple circuit, single, multipolar drum. The number of coils

is 96, and there are four poles, so that the average pitch will be 48, and the back pitch 47, the front pitch 49, from which a winding diagram similar to Plate 19, page 183. may be worked out on the drawing board.

We will now proceed to calaulate the reluctance of the magnetic path offered by the air gap, teeth and slots, and the combined effects of the field and armature ampere turns on the flux in this part of the magnetic circuit.

By equation 78, page 202, the demagnetizing armature ampere turns per pole will be,

$$\frac{576 \times 69 \times .3}{4 \times 2 \times 4} = 373;$$

The difference between the effective ampere turns on the weak and the strong pole tip is 2a (S'I') = 1730, where 72 is the number of armature turns per pole and 17.25 the value of the current flowing in them.

We will now calculate the reluctance of the air gap, teeth and slots.

1	2	3	4	5	6	7
B_t	B_b	H_{av}	B_{ag}	$(Si)_{ts}$	$(Si)_{ag}$	$(Si)_t$
4000	6220	1.75	1558	3.31	295	298.3
5000	8280	2.10	1949	3.98	369	373.0
6000	9935	2.30	2339	4.36	443	447.4
8000	13230	3.90	3114	7.40	589	596.4
10000	16540	9.70	3887	18.40	737	755.4
12000	19890	45.50	4677	86.40	886	972.4
13000	21540	129.00	5050	245.00	956	1201.0
14000	23190	189.00	5448	358.00	1031	1389.0
15000	24830	318.50	5850	605.00	1110	1715.0
16000	26540	463.60	6235	937.00	1180	2117.0
17000	28130	815.80	6640	1169.00	1259	2428.0
18000	29810	929.00	7070	1572.00	1340	2912.0
19000	31490	978.00	7480	1856.00	1420	3276.0

Plotting the average air gap densities as given in column 4 against the corresponding required ampere turns as given by column 7, as abcissae, we get the curve shown on the following page.

We may now calculate the commutating field density required under the weak pole tip at full load, and by applying this to the curve, we find the value of the necessary effective full load ampere turns on the leading pole tip, $(Si)_{lp}$.

During the time the short circuited current is flowing from one segment to the next, the current density will be,

$$\frac{4 \times 17.25}{1.414} = 43.8.$$

$$r'_b = \frac{4 \times .024}{1.414} = .06775,$$

where .024 is the resistance per sq. in. for a single contact when the current density is 43.8 amperes per square inch.

The resistance of a single coil on the armature is,

$$\frac{.2126}{21} = .01012 \text{ ohms},$$

So that the resistance from one segment to the brush across to the next segment and through the coil will be,

$$.06775 + .01012 = .07787 \text{ ohms};$$

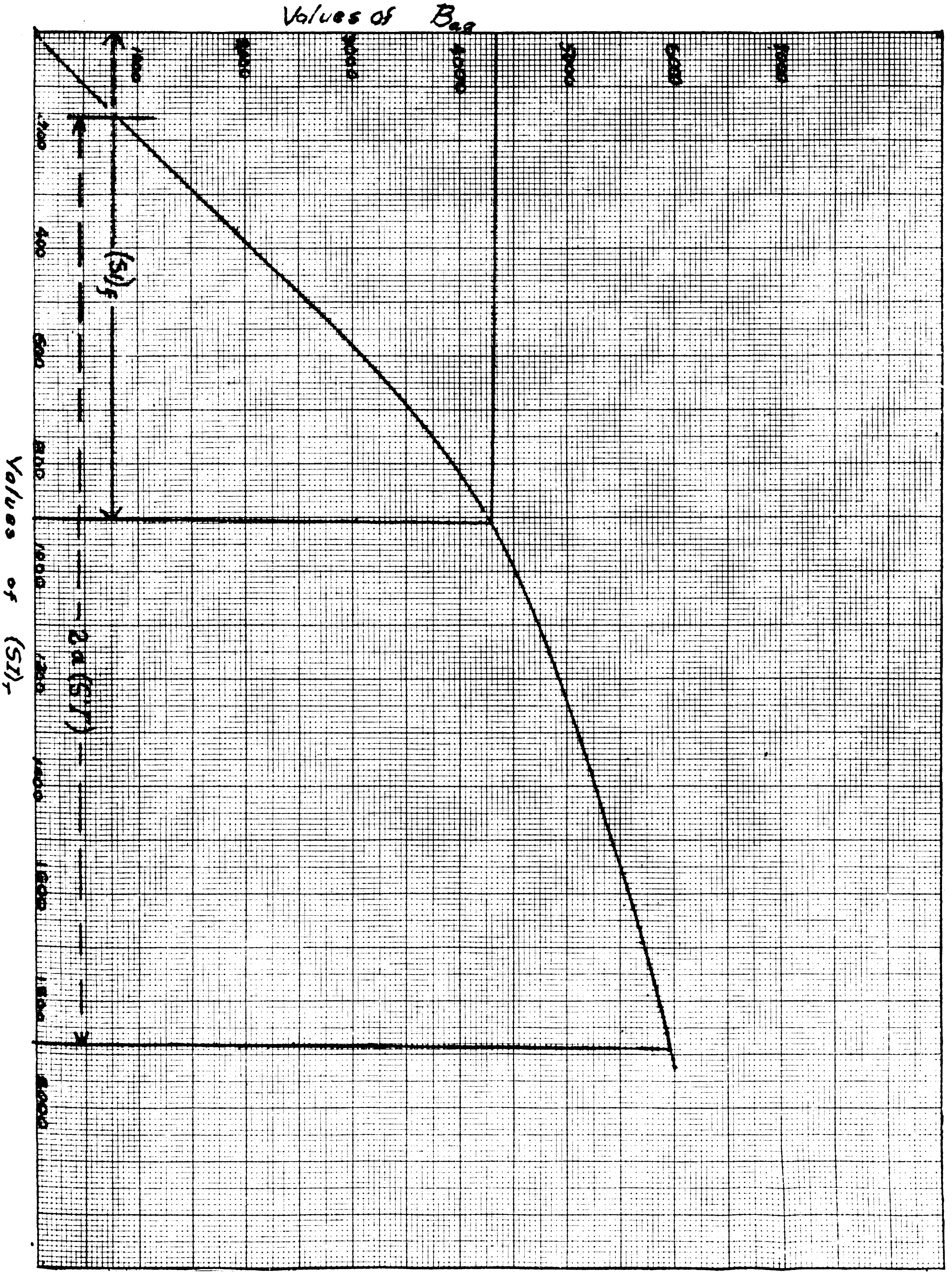
according to equation 84, page 207, the developed voltage during commutation must be,

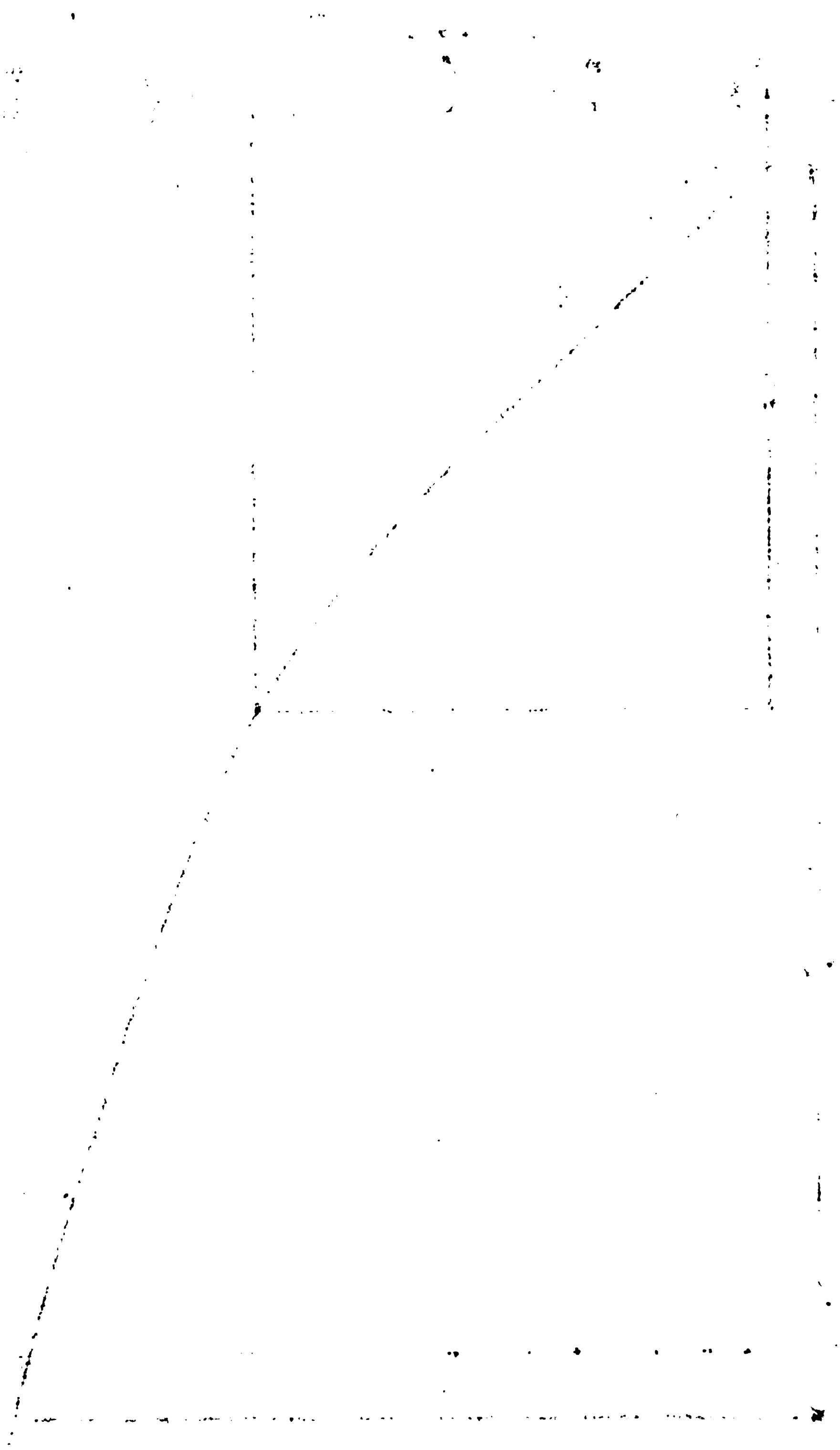
$$17.25 \times .07787 = 1.343 \text{ volts}.$$

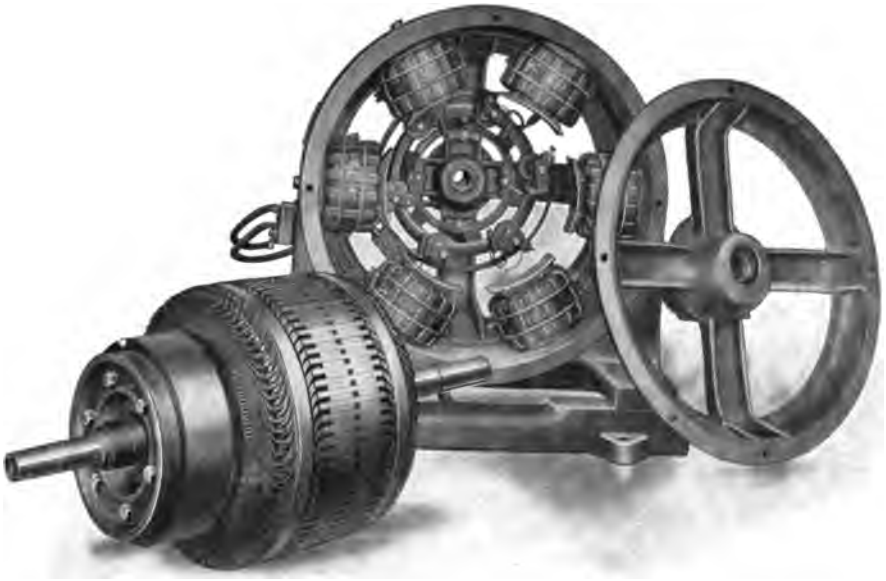
The peripheral velocity of the conductors in cm. per second is,

$$V' = \frac{1800 \times \pi \times (9.25 - .9375) \times 2.54}{60}$$

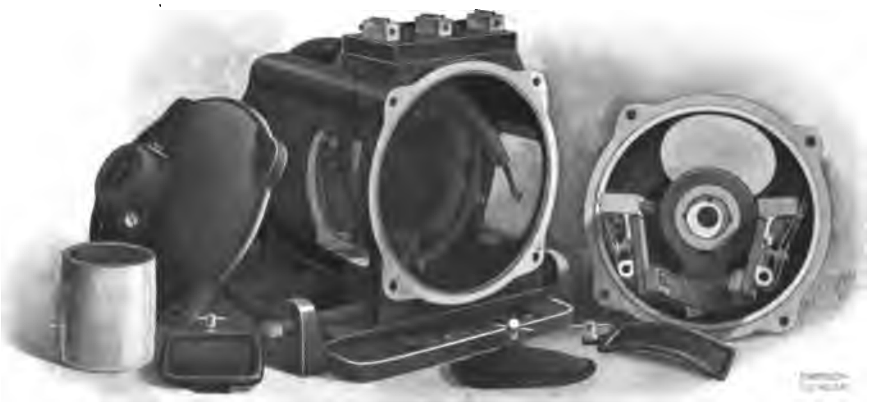
= [illegible] cm. per second


Values of B_{ag}
1000
2000
3000
4000
5000
6000
7000
Values of $(SI)_r$
200
400
600
800
1000
1200
1400
1600
1800
2000
$(SI)_f$
$2a(SI)$





GENERAL ELECTRIC CO. 6 POLE MOTOR.



EMERSON ELECTRIC MFG. CO. 6 POLE MOTOR.

The net length of the iron in the armature in cm. = 2.54 x 5.51 = 14.0 cm. Then by equation 85, page 208, the leading pole tip density in order to reverse the full load current in the coil must be,

$$B_c = \frac{10^8 \times 1.343}{14 \times 1988 \times 3 \times 2} = 805 \text{ gausses.}$$

The abcissa corresponding to the ordinate of 805 gausses is 147, the effective full load ampere turns on the leading pole tip.

Laying off from this point, the value of 2a(S'I') = 1730, we get the effective full load ampere turns on the trailing pole tip = 1875 and the corresponding ordinate is the density under the strong pole tip at full load = 7,600 gausses.

BuBy use of the planimeter, we find the area of the space enclosed by the abcissae of the two pole tips to be 25.9 sq.in., equal to 163. sq. cm. The length of the abcissa 2a(B'I') is 17.3 cm., so that the average ordinate of the area is

$$\frac{163.0}{17.3} = 9.43 \text{ cm.}$$

which corresponds to a density of 4,690 gausses, which would be the average full load air gap density.

The drop in the armature winding has been found to be 3.78 volts; that in the brush contacts 1.828 volts; and assuming the drop in the series winding to be .75 of that of the armature winding, the total internal drop in the machine at full load will be,

$$3.78 + 1.828 + 2.84 = 8.45 \text{ volts,}$$

so that the full load developed voltage must be 160 + 8.45 = 168.45 volts. The average full load air gap density must then be

$$4,14 \quad \frac{4,130 \times 168.45}{160} = 4,360 \text{ gausses.}$$

Comparing this value with that just found from the curve we see that the density compares favorably with the average full load density as found from the curve.

Assuming a leakage coefficient of 1.16, in accordance with Table. XXXVII, page 210, and a no load density of 10,000 gausses in the field cores. The net area of a field core will be, by equation 86, page 209,

$$\frac{4,130 \times 224.25 \times 1.16}{10,000 \times 6.45} = 16.68 \text{ sq. in.,}$$

and the width of a pole will be, within the coil, assuming 92 % of the length to be iron, by equation 87, page 210,

$$\frac{16,68}{6.625 \times .92} = 2.75 = 2\text{-}3/4 \text{ inches.}$$

The full load density in the field cores will then be,

$$\frac{10,000 \times 168.45}{160} = 10,520 \text{ gausses.}$$

Using cast iron in the yokes and assuming a no load yoke density of 5,700 gausses, by equation 88, page 210, the area of cross section of the yoke will be,

$$\frac{4,130 \times 224.25 \times 1.16}{2 \times 5,700 \times 6.45} = 14.61 \text{ sq. in.}$$

The length of the pole is 6.625 inches, and in order to make the yoke project over the field coils, we will make it 9 inches in width and elliptical in section. The area of the ellipse is 14.61 sq. in. and the major axis 9 inches; the minor axis, the maximum thickness of the yoke is then,-

$$14.61 \times 4 = 2.06, \text{ say } 2 \text{ inches.}$$

The full load density in the yoke will be,-

$$\frac{5,700 \times 168.45}{160} = 6000 \text{ gausses.}$$

Assuming a radial length of pole of 4-3/4 inches, and making the proper allowance for the flux to pass out to the pole tips, the dimensions of the pole stamping will be as shown in Fig. 62. The core will be held together by insulated bolts passing through the circular holes, plates about 1/4 in. in thickness being used on the ends. The poles will be secured to the yoke by a bolt which passes through the yoke and screws into a square piece of wrought iron which is placed in the square hole passing through the pole parallel to the shaft.

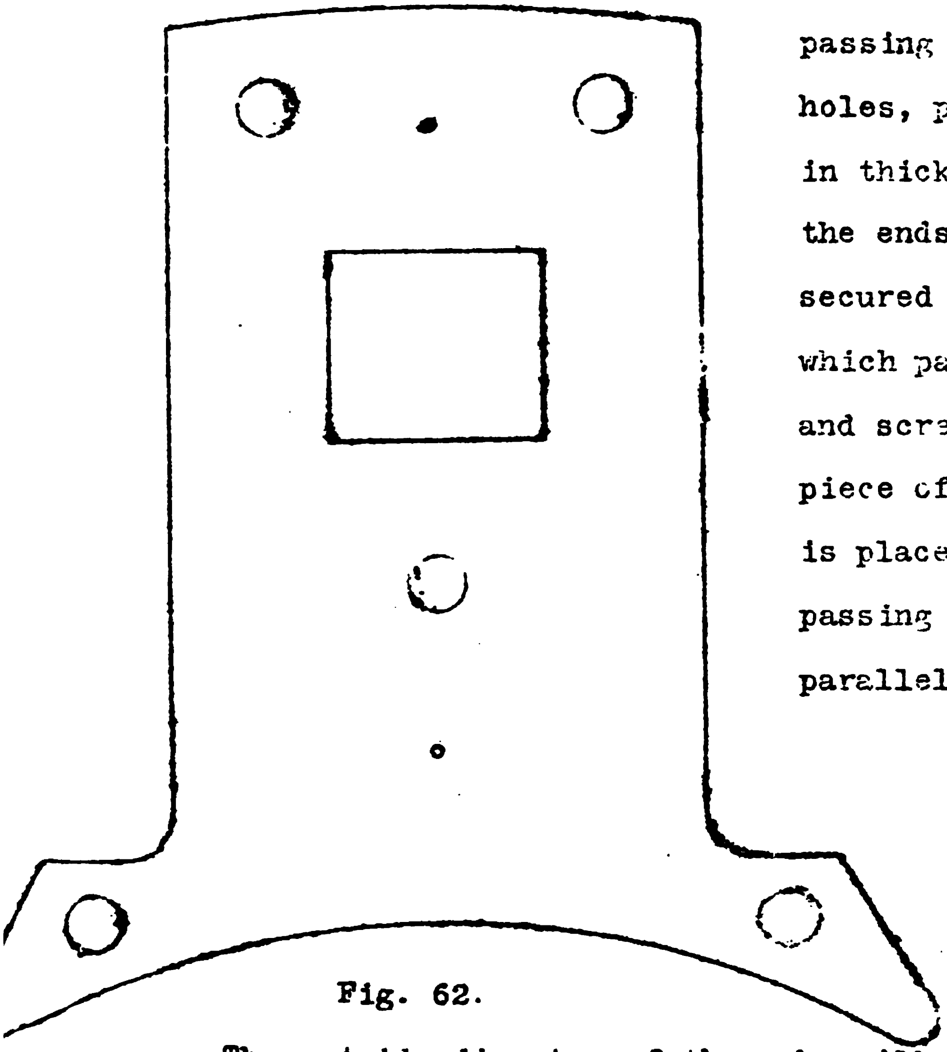


Fig. 62.

The outside diameter of the yoke will then be,

$$9.25 + 3/16 + 2(4.75) + 4 = 22\text{-}15/16 \text{ inches.}$$

A scale drawing of a portion of the magnetic circuit may now be made on the drawing board, as directed on page 136, from which the lengths of the magnetic paths may be taken.

When this has been done, the required no load and full load ampere turns, and the shunt and series winding may be calculated.

It will be well to tabulate the values as follows:

Portion of Circuit.	Material	No Load density	Value of H	Length in cm.	Gilberts	(Si)
Yoke	Cast Iron	5,700	19	21.78	413.0	330.0
Pole	Sht. Steel	19,000	6	12.25	73.4	58.6
Ar. Core	" "	9,500	5.5	5.60	30.8	24.5
Air gap, teeth & Slots,		4,130	taken directly from curve			835.0
			Total no load ampere turns,			1248.1

Allowing a thickness of 3/8 inch for the field spool and its insulation, the length of an inside turn will be,-

$$2(6.625 + .75) + 2(2.75 + .175) = 21.7 \text{ inches.}$$

Assuming a depth of winding of 3/4 inch, the length of an outside turn will be 8 x .75 = 6 inches longer than an ouinside turn, so that the mean length of a turn will be,-

$$\frac{21.7 + 21.7 + 6}{2} = 25.15 \text{ inches.}$$

Upon the assumption that 20 % of the e.m.f. is taken up by the field rheostat, the voltage on one field coil will be,-

$$\frac{180 \times 8}{4} = 32 \text{ volts.}$$

By equation 91, page 212, the size of the shunt field wire should be,

$$\frac{12.02 \times 25.15 \times 1248}{12 \times 32} = 980 \ (m);$$

The nearest size is # 20 B. & S, having a cross section of 1022 (m)

The radiating surface of one field coil will be as follows, For the sides of the coil, assuming the length of the coil

to be 2.5 inches; the area will be 28.6 x 2.5 = 71.7 sq. in. One end of a coil will have an area of 25.15 x .75 = 19.1 sq. in. so that the total radiating area will be 90.8 sq. in.

By equation 92, page 213, assuming a rise of temperature of 40 degrees above the air, the allowable current will be,

$$\frac{90.8 \times 40}{83 \times 32} = 1.26$$ amperes, and the (m) per ampere will be, $\frac{1022}{1.26} = 815$ (m) per ampere, which is a good value.

The number of shunt turns in one coil will be, $\frac{1248}{1.26} = 990$, which will require a winding space of $\frac{990}{566.9} = 1.76$ sq. in. We have allowed a space of .75 x 2.5 = 1.875, which checks sufficiently close. The resistance of one field coil will be,

$$\frac{25.15 \times 990 \times 12.02}{12 \times 1022} = 24.4 \text{ ohms},$$

and the current which would flow with 32 volts impressed will be $\frac{32}{24.4} = 1.22$ amperes. The watts loss in the shunt winding will be, including that in the rheostat, 1.26 x 160 = 201.5 watts.

We may now proceed with the calculation of the series winding.

We shall now calculate the required full load ampere turns to be supplied by the series and shunt winding acting together.

Portion of Circuit.	Full load Density	Value of H.	Length in cm.	Gilberts	(Si)
Yoke	6000	22.8	21.78	498	397.0
Pole	10520	6.5	12.25	97.7	63.4
Arm. Core	10000	6.0	5.6	33.6	26.7
Air Gap, tooth	4360	and slots, taken from curve,			930.0
					1417.1
Armature demagnetizing ampere turns per pole,					373.0
Total full load ampere turns per pole,					1790.1

Since the full load terminal voltage is to the same as the no load voltage, the shunt ampere turns will remain practically constant from no load to full load, so that by equation 95, page 215, the series ampere turns per pole will be,

1790.1 - 1248.1 = 542, and by equation 96, page 215, the number of series turns per pole will be,

$$\frac{542}{69 - 1.26} = 8$$ turns per pole; for the reasons given on page 215, we will use 8.5 turns per pole.

The mean length of a turn of the series winding will be the same as that of the shunt winding, so that the total length of the series winding, allowing 6 inches for connections between coils, and 3 feet for each connection to the terminals,-

$$\frac{(4 \times 8.5 \times 25.15) + (3 \times 6) + (2 \times 36)}{12} = 78.9 \text{ feet}$$

Assuming a current density of 850 (m) per ampere, the cross section of the series conductor will be 67.74 x 850 = 57,750 (m) = 43,800 |m|. The resistance of the series winding will be,-

$$\frac{12.02 \times 78.9}{55{,}750} = .01644 \text{ ohms;}$$

The drop at full load will be .01644 x 67.74 = 1.12 volts, and the I^2R loss will be,

$$\frac{1.12 \times 67.74}{4} = 19$$ watts per coil, or a total of 76 watts.

We will make the width of the series conductor equal to the depth of the shunt winding, and wind the strips on edge, one layer deep, so that the outer dimensions of the shunt and series coils will be the same. The thickness of the conductor must then be,

$$\frac{43{,}800}{.75 \times 1000 \times 1000} = .0584 \text{ inches.}$$

Allowing for a thickness of insulation on each conductor, on each side, the thickness of the insulated oncductor will be

$$.0584 + (2 \times .03) = .1184 \text{ inches.}$$

And the winding area re quired by each coil will be,-

$$.1184 \times 9 \times .75 = .801 \text{ square inches.}$$

An air space will be left between the series and shunt coils, and also between the series coil and the end of the spool, so that the radiating surface of one coil will be,-

$$(2 \times 25.15 \times .75) + (28.6 \times .1184 \times 8.5) = 64.6 \text{ sq.in.}$$

The temperature rise of the series coils will then be,

$$\frac{19.0 \times 83}{64.4} = 24.5^{\circ} \text{ Centigrade above the air.}$$

Assuming the loss due to bearing friction and windage to be 1.5 % of the output at full load, we have 10.5 x 1000 x .01 = 105 watts. We may now calculate the losses for any givon load and consequently the efficiency at that load. These calculation tabulated are as follows.

Load in %	Arm. I^2R	Brushes I^2R	Brushes Arm I^2R	Shunt I^2R	Core Loss	Brushes Bearing Friction.	Total Losses	Eff. in %.
0	0.	0.	0.	201.5	415	235	851.5	0.
25	18.6	12.8	31.4	201.5	415	235	882.9	74.7
50	74.5	51.0	125.5	201.5	415	235	977.0	84.4
75	169.4	116.1	285.5	201.5	415	235	1137.0	87.3
100	298.0	202.1	500.1	201.5	415	235	1351.6	88.7
125	460.0	316.0	776.0	201.5	415	235	1627.0	89.0
150	672.0	462.0	1134.0	201.5	415	235	1985.0	89.1

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From the data contained in the above table for armature I^2R and core loss for the different loads, the temperature rise of the armature at different loads is found to be as follows.

Load in per cent.	0.	25.	50.	75.	100.	125.	150.
Temp. rise above air,	24.5	25.6	29.0	34.4	42.0	51.7	64.0

From the above data curves of efficiency and temperature rise for continuous operation, at the different loads may be plotted, and the variable and constant losses shown, as indicated on page 252.

The mechanical details may be worked out as the work proceeds on the drawing board. The brush holders, method of mounting the stampings of the armature core should receive special attention.

When the calculations have thus been completed, it will be found convenient to tabulate the results, using blank forms as indicated on the following pages.

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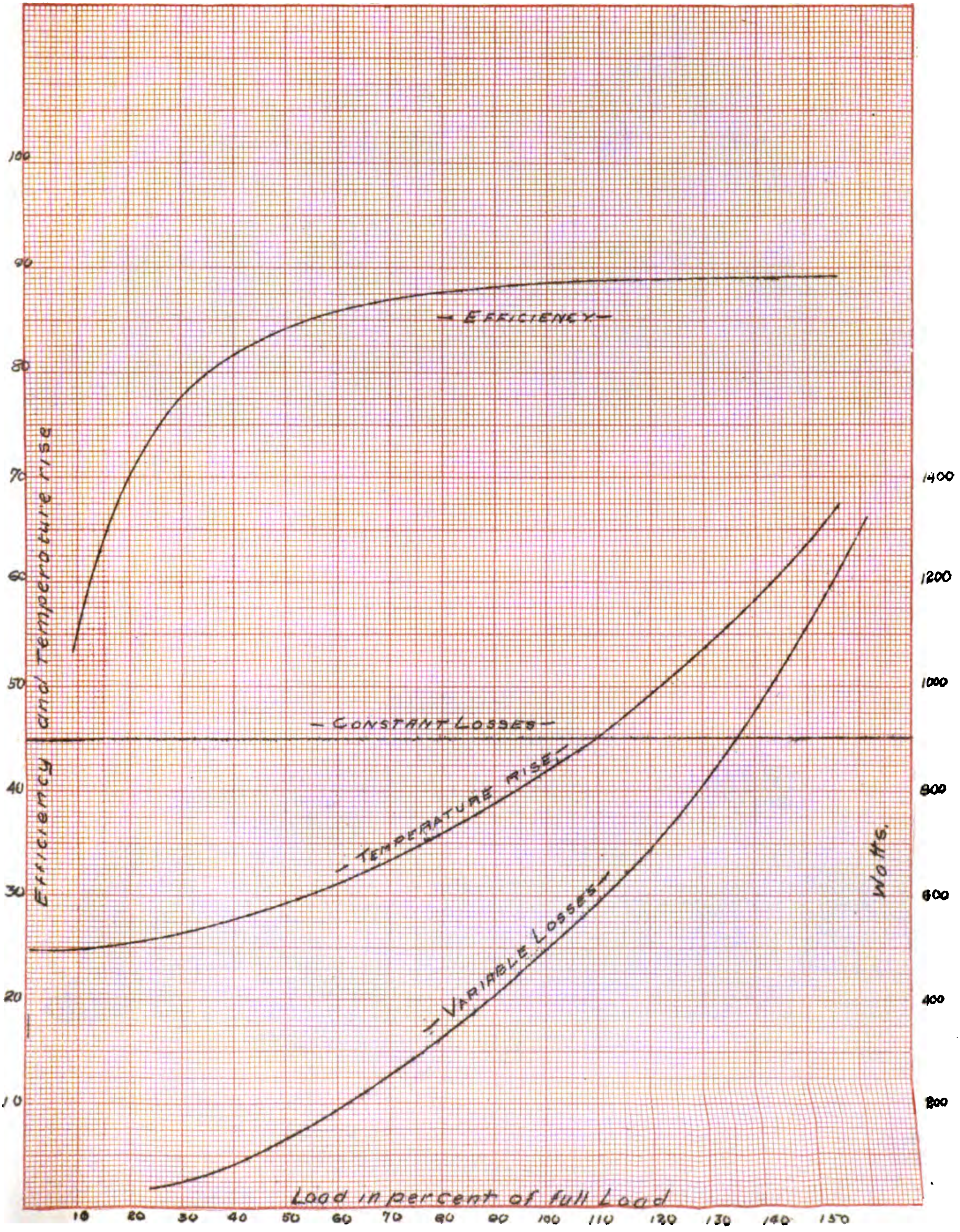
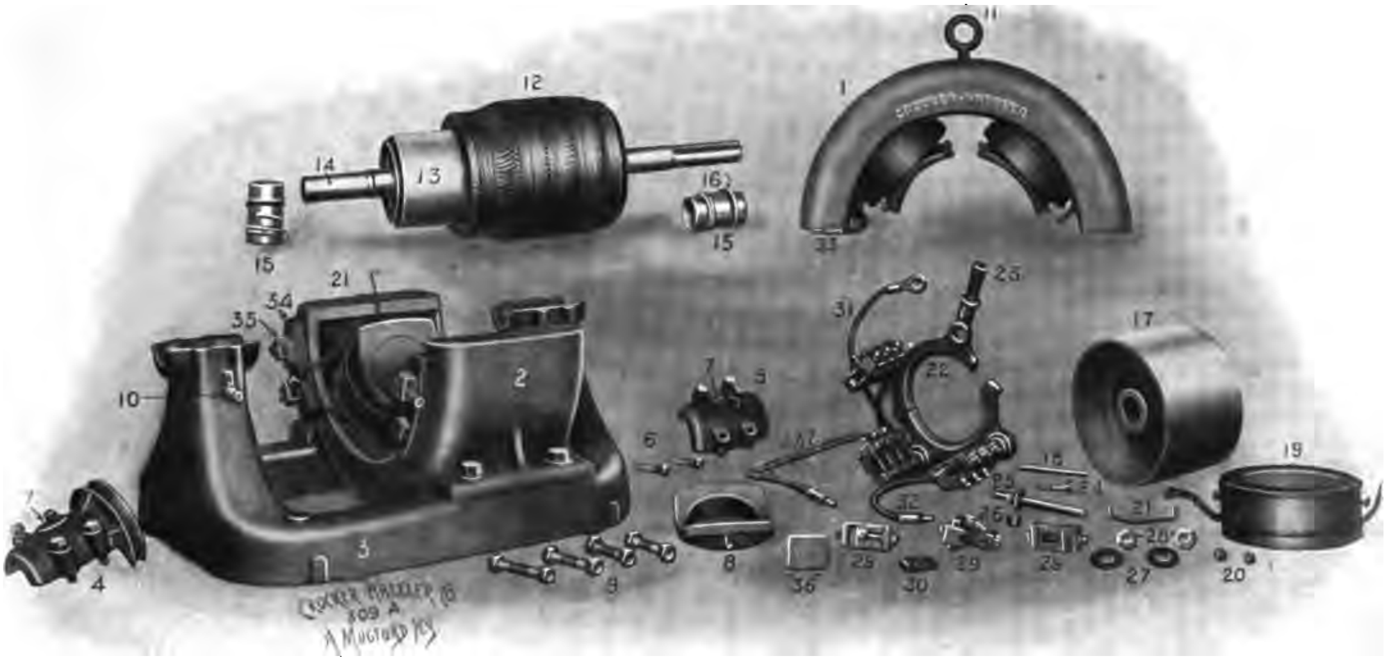
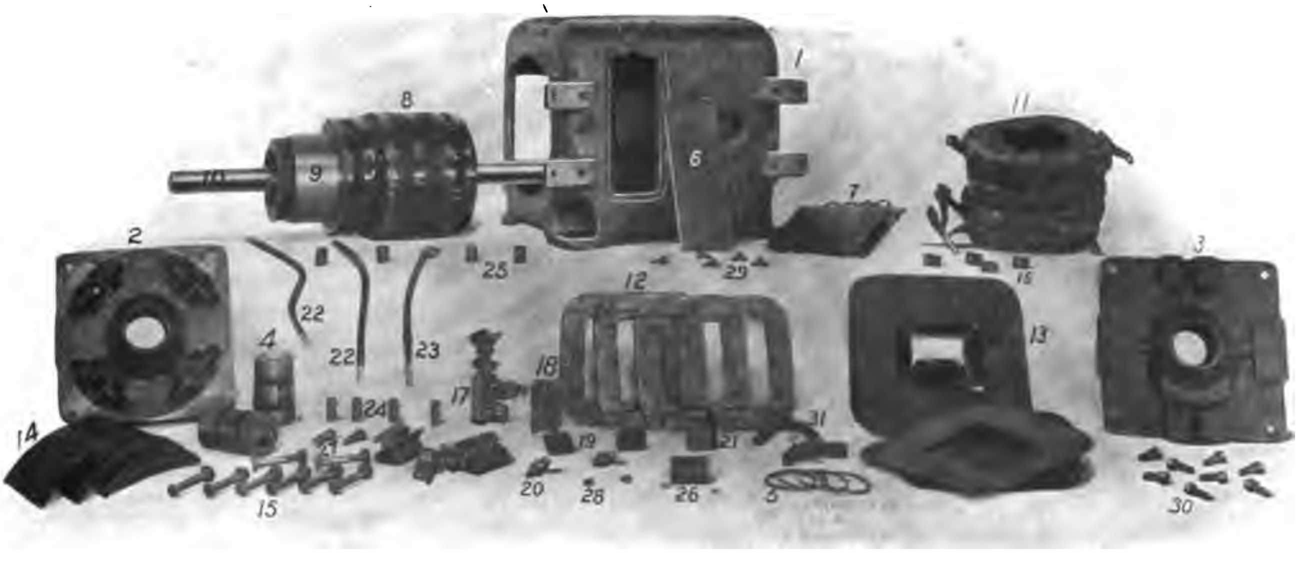


100
90
80
70
60
50
40
30
20
10
Efficiency and Temperature rise
1400
1200
1000
800
600
400
200
Watts.
EFFICIENCY
CONSTANT LOSSES
TEMPERATURE RISE
VARIABLE LOSSES
Load in percent of full Load
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150



PARTS OF A DIRECT CURRENT GENERATOR. CROCKER-WHEELER CO.



PARTS OF A MILL MOTOR. CROCKER-WHEELER CO.

SPECIFICATIONS.

Number of poles, ______
Kilowatts, ______
Revolutions per minute, ______
Frequency in cycles per second, ______
Terminal volts, no load, ______
Terminal volts, full load, ______
Amperes, full load, ______

DIMENSIONS.

ARMATURE:

Diameter over all, ______
Length over conductors, ______
Diameter at bottom of slots, ______
Internal diameter of core, ______
Length of core over all, ______
Effective length, magnetic iron, ______
Pole pitch at armature surface, ______
Insulation between sheets, ______
Thickness of sheets, ______
Depth of slot, ______
Width of slot at root, ______
Width of slot at surface, ______
Number of slots, ______
Minimum width of tooth, ______
Width of tooth at armature face, ______
Width of conductor, ______
Depth of conductor, ______
Number of ventilating ducts, ______
Width of each ventilating duct, ______
Effective length of core ÷ total length, ______
Diameter of spider, external in inches, ______
Diameter of spider, internal in inches, ______
Length of spider, ______

MAGNET CORE:

Length of pole face, ______
Length of pole arc, ______
Pole arc ÷ pitch, ______
Thickness of pole - piece at edge of core, ______
Radial length of magnet core, ______
Width of magnet core, ______
Thickness of magnet core, ______
Diameter of bore of field, ______
Length of air gap. ______

SPOOL:

Length over flanges, ______
Length of winding space, ______
Depth of winding space, ______

YOKE:

Outside diameter, ______
Inside diameter, ______
Thickness, body, ______

Length along armature,

SHAFT AND BEARINGS:

Diameter of shaft inside spider,
Diameter of shaft in bearings.
Length of bearing surface,
Length of shaft over all,
Length between bearing centers,

COMMUTATOR:

Diameter,
Number of segments,
Number of segments per slot,
Width of segment at commutator face,
Width of segment at root,
Depth of segment, total,
Depth of segment, useful,
Thickness of mica insulation,
Available length of surface of segment,
Cross-section of commutator leads,

BRUSHES:

Number of sets,
Number in one set,
Width,
Thickness,
Area of contact, of one brush,
Type of brush,

MATERIALS.

Armature core,
Armature spider,
Armature shaft,
Armature Bearings,
Armature Conductors,
Commutator Segments,
Commutator leads,
Commutator spider,
Pole shoe,
Yoke,
Magnet core,
Brushes,
Brush holders,
Base.

TECHNICAL DATA.

Armature, no load voltage,
Number of face conductors,
Conductors per slot,
Number of circuits,
Style of winding,
Gramme ring or drum,
Type of construction of winding,
Pitch of coil, front,
Pitch of coil, back,
Mean length one armature turn,

Total armature turns,
Turns in series between brushes,
Length between brushes,
Cross-section, one armature conductor,
Ohms per 1000 ft. at 25 deg. Cent.
Resistance between brushes at 25 deg. Cent.
Resistance between brushes at 65 deg. Cent.
Volts drop in armature at 65 deg. Cent.
Volts drop in brush contact,
Volts drop, series winding,
Terminal voltage, full load,
Total internal voltage, full load,
Circular mils per ampere in armature winding,
Circular mils per ampere in commutator connections

COMMUTATION:

Amerage voltage between commutator segments,
Armature turns per pole,
Amperes per turn,
Armature ampere turns per pole,
Segments lead of brushes,
Percentage lead of brushes,
Percentage demagnetizing ampere turns,
Percentage distorting ampere turns,
Demagnetizing ampere turns per pole,
Distorting ampere turns per pole,
Frequency of commutation (cycles per second)
Number of conduotors per group simultaneously undergoing commutation,
Number of coils simultaneously short-circuited per brush,
Turns per coil,
Flux per ampere turn per inch length armature lamination,
Flux linked with ..... turns,
Inductance in one coil, in henrys,
Reactance short-circuited coil,
Reactance voltage,

MAGNETIC DATA.

Coefficient of magnetic leakage,
Maxwells entering armature per pole-piece at no load and ..... volts,
Maxwells entering amarmature per pole-piece at full load and ..... internal volts,

ARMATURE CORE:

Section,
Length (magnetic) per pole,
Density at no load,
Density at full load,
Ampere turns per inch length, no load,
Ampere turns per inch length, full load,
Ampere turns, no load,
Ampere turns, full load,

[illegible] 1953

[illegible]

[illegible]

[illegible]

[illegible] COPY

[illegible]

[illegible]

[illegible]

[illegible]

TEETH:

Number transmitting flux from one pole piece, ______
Section at roots, ______
Length, ______
Apparent density at no load, ______
Apparent density at full load, ______
Corrected Density at no load, ______
Corrected density at full load, ______
Ampere turns per inch length, no load, ______
Ampere turns per inch length, full load, ______
Ampere turns, no load, ______
Ampere turns, full load, ______

GAP:

Section at pole face, ______
Length of gap, ______
Density at pole face, no load, ______
Density at pole face, full load, ______
Ampere turns, no load, ______
Ampere turns, full load, ______

MAGNET CORE:

Section, ______
Length (Magnetic) ______
Density, no load, ______
Density, full load, ______
Ampere turns per inch length, no load, ______
Ampere turns per inch length, full load, ______
Ampere turns, no load, ______
Ampere turns, full load, ______

MAGNET YOKE:

Section, ______
Length per pole, ______
Density, no load, ______
Density, full load, ______
Ampere turns per inch length, no load, ______
Ampere turns per inch length, full load, ______
Ampere turns, no load, ______
Ampere turns, full load, ______

AMPERE TURNS PER SPOOL.

Armature core, ______
Armature teeth, ______
Air gap, ______
Magnet Core, ______
Yoke, ______
Demagnetizing ampere turns per pole piece at full load, ______
Allowance for increase in density through distortion, ______
Total ampere turns at full load of ..... amperes and ..... terminal volts, ______
Ampere turns per pole-piece on armature, ______

CALCULATION OF SPOOL WINDINGS.

SHUNT:

Mean length of one shunt turn in inches, ______
Ampere turns per shunt spool at full load, ______
Radiating surface one shunt spool, ______
Watts radiated per sq. inch per degree rise Cent. ______
Shunt watts per spool at 65 deg. Cent. ______
Pounds copper per coil, ______
Current in shunt coils, ______
Turns per shunt spool, ______
Length of turns, ______
Pounds per 1000 feet, ______
Current density circular mils per ampere, ______
Length of the portion of winding space available for shunt coil, inches, ______
Depth of winding, inches, ______
Cross-section conductors, ... circular mils, ______
Current density, ... circular mils per ampere, ______
Resistance of ... spools at 25 deg. Cent. ______

SERIES:

Series turns per spool, ______
Series ampere turns per pole, ______
Current density - circular mils per ampere, ______
Series I^2R loss at 65 deg. Cent. ______
Weight series copper per spool, ______

ESTIMATED CORE LOSS.

Total weight armature laminations, ______
Cycles per second, ______
Kilogausses density in core, ______
Cycles x Kilogausses, ______
Corresponding core loss per pound, ______
Total core loss, ______

THERMAL CALCULATIONS.

ARMATURE:

I^2R loss at 65 deg. Cent. ______
Core loss full load, ______
Total armature loss, ______
Peripheral radiating surface armature, ______
Watts per square inch radiating surface armature, ______
Peripheral speed armature, feet per minute, ______
Watts radiated per sq. inch per degree Cent. rise in temperature, ______
Temperature rise in deg. Cent. at full load, ______

SPOOL:

Total I^2R loss at 65 deg. Cent. per spool, ______
Peripheral radiating surface one spool, ______
Watts per square inch of radiating surface per degree Centigrade rise in temperature, ______
Temperature rise in degrees Centigrade at full load, ______

COMMUTATOR:

Area bearing surface all positive brushes, ________
Amperes per square inch of brush bearing surface, ________
Ohms per square inch positive and negative contact of ..... brushes, ________
Brush resistance, positive + negative, ________
Volts drop at brush contacts, ________
I^2R at brush contacts, ________
Brush pressure, ________
Coefficient of friction, ________
Peripheral speed of commutation in feet per minute, ________
Brush friction, ________
Total commutator loss, ________
Radiating surface commutator, ________
Watts per square inch of radiating surface, ________
Temperature rise in deg. Cent. ________

EFFICIENCY CALCULATIONS.

Output at full load, ________
Core loss, ________
I^2R armature at 65 deg. Cent. ________
Commutator and brush loss, ________
Shunt spools I^2R at 65 deg. Cent.
Shunt rheostat, ________
Series spools - I^2R at 65 deg. Cent. ________
Series rheostat I^2R at 65 deg. Cent. ________
Bearing friction and windage (estimated) ________
Total input, ________
Commercial efficiency at full load and 65 deg. Cent ________

WEIGHT (POUNDS)

COPPER:

Armature conductors, ________
Commutator segments, ________
Shunt spools, ________
Series spools, ________

IRON OR STEEL:

Armature laminations, ________
Armature spider, ________
Commutator spider, ________
Pole cores and shoes, ________
Yoke, ________
Shaft, ________
Bearings and Pedestals, ________
Base, ________

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